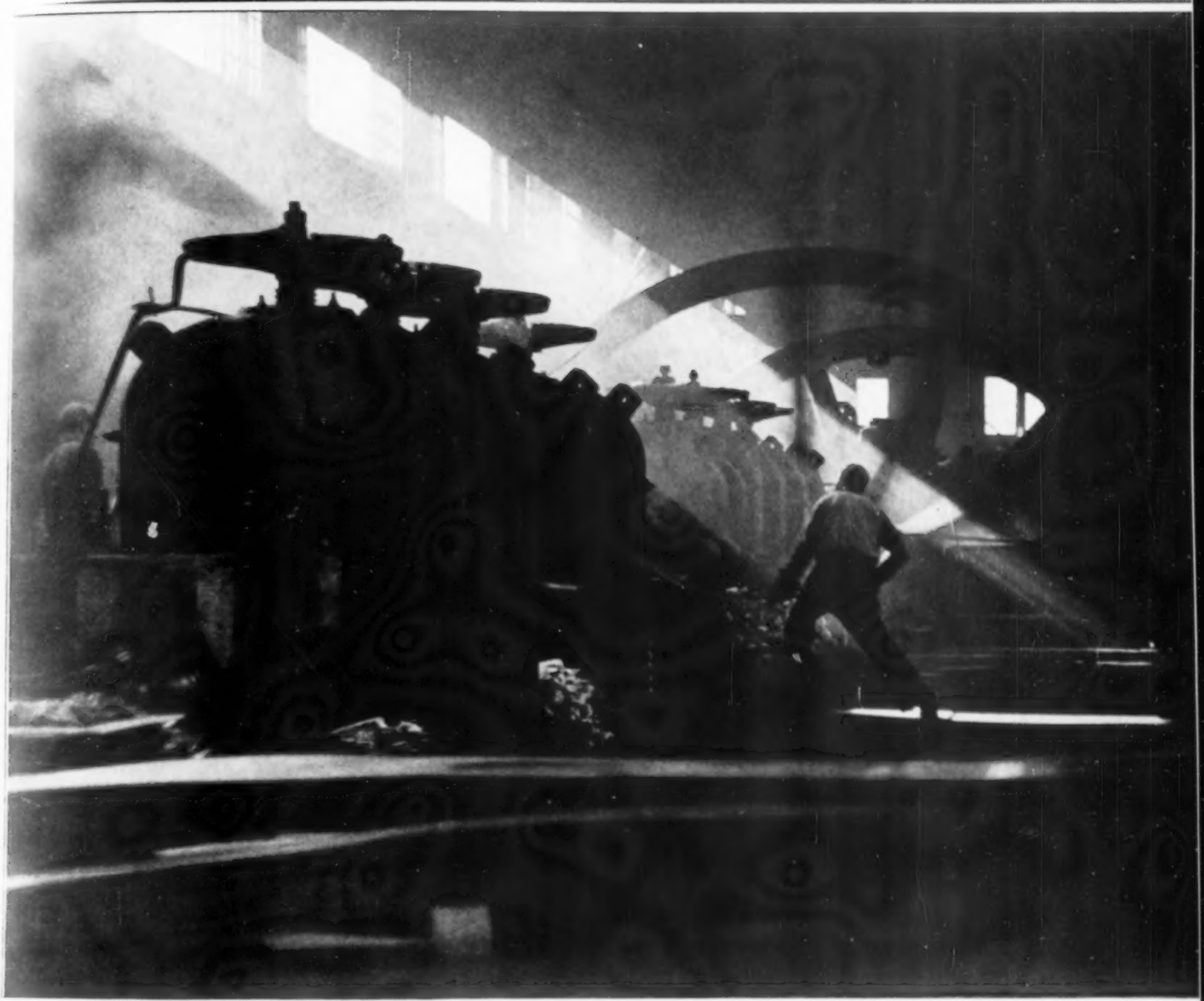
Metal Progress

AMERICAN SOCIETY FOR METALS



FEBRUARY
ISSUE
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METAL PROGRESS

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FEBRUARY, 1939 VOLUME 35 NUMBER 2

LARGE MFG. CO. SECURES DEFINITE SAVINGS
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HELPS SECURE QUICK GOVERNMENT OK
A company specializing in government aviation work finds Ryerson alloy steel test reports enable them to get quick approval of steel by government officials and inspectors.
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COMPOSITE METALS

by carbon-arc welding

By Robert E. Kinkead
Consulting Engineer, Welding
Cleveland, Ohio

USE OF COMPOSITE MATERIALS IS reflected in many and varied forms. Galvanized wire, pipe and sheets combine the strength and low cost of steel with the corrosion resistance of zinc. Steel is coated with glass, rubber, copper, brass, paint lacquer, alloys for hard facing — all for the purpose of increasing utility and serviceability.

The actuating motive is usually one of reducing the initial cost or the cost of use. Thus, copper-clad steel wire for railway signal bonds lasts 10 to 20 times as long as pure copper bonds of the same initial cost, on account of the resistance of the steel core to destruction by vibration. Nickel-clad steel used for making vessels to handle food products costs about half as much as solid nickel plate for the same purpose. The composite has greater strength and, since only one side can possibly come in contact with food, serves the purpose exactly as well as solid nickel plate.

The chromium-nickel alloys which have been developed in recent years have found many uses. The 18% chromium, 8% nickel alloys now comprise the most popular group of stainless steels. The wider use of these almost noble metals is inhibited by their high price; at $580 per ton base price, 18-8 costs roughly 14 times as much as carbon steel. For about half the known uses, low carbon steel with a properly applied cladding of 18-8 would serve the purpose just as well as solid stainless. The price might be half as much for the composite material as for the solid stainless.

While the advantages of composites of low carbon steel and very expensive metals are striking, the economies of composite metals are by no means restricted by such cases. Thus, one of the serious problems which has been encountered in the design and construction of welded steel machinery has been a lack of low cost composite metals. Machined surfaces on low and medium carbon steel are expensive as compared with machine work on steel having 0.40% carbon, and it is a fact that lubrication is difficult and wear unsatisfactory for rapidly moving parts made of low carbon steel. Building up higher carbon, wear resistant surfaces by manual welding or even automatic arc welding machines is, in many cases, prohibitively expensive. On the other hand, if the parts to be welded together are made of steel having the machining and wearing qualities of 0.40% carbon steel, it becomes necessary to preheat before welding to prevent the joint from cooling rapidly and cracking.

A notable example is the problem of making welded steel gear wheels. The rim needs

A paper (slightly abridged) which received third grand award in $200,000 competition sponsored by James F. Lincoln Arc Welding Foundation, 1938

to be 0.40% carbon steel or above to cut the gear teeth successfully. The remainder of the gear (arms and hub) may be medium carbon steel. The job of handling the assembly and welding it while hot is so difficult that most manufacturers prefer to buy cast steel wheels. If a line of bar stock were available from the steel mills with say half of the thickness made of 0.40% to 0.50% carbon steel and the remainder in the 0.15% to 0.25% carbon range, most manufacturers would make their own gear blanks by welding. The rim would be formed hot with the higher carbon steel on the outside. The assembly of the gear wheel could then be made by welding the arms to the low carbon side without preheating.

The above described composite would also be useful in welded steel machinery for guides, ways on planers, and in many other places on the machine where a surface is machined and subjected to wear.

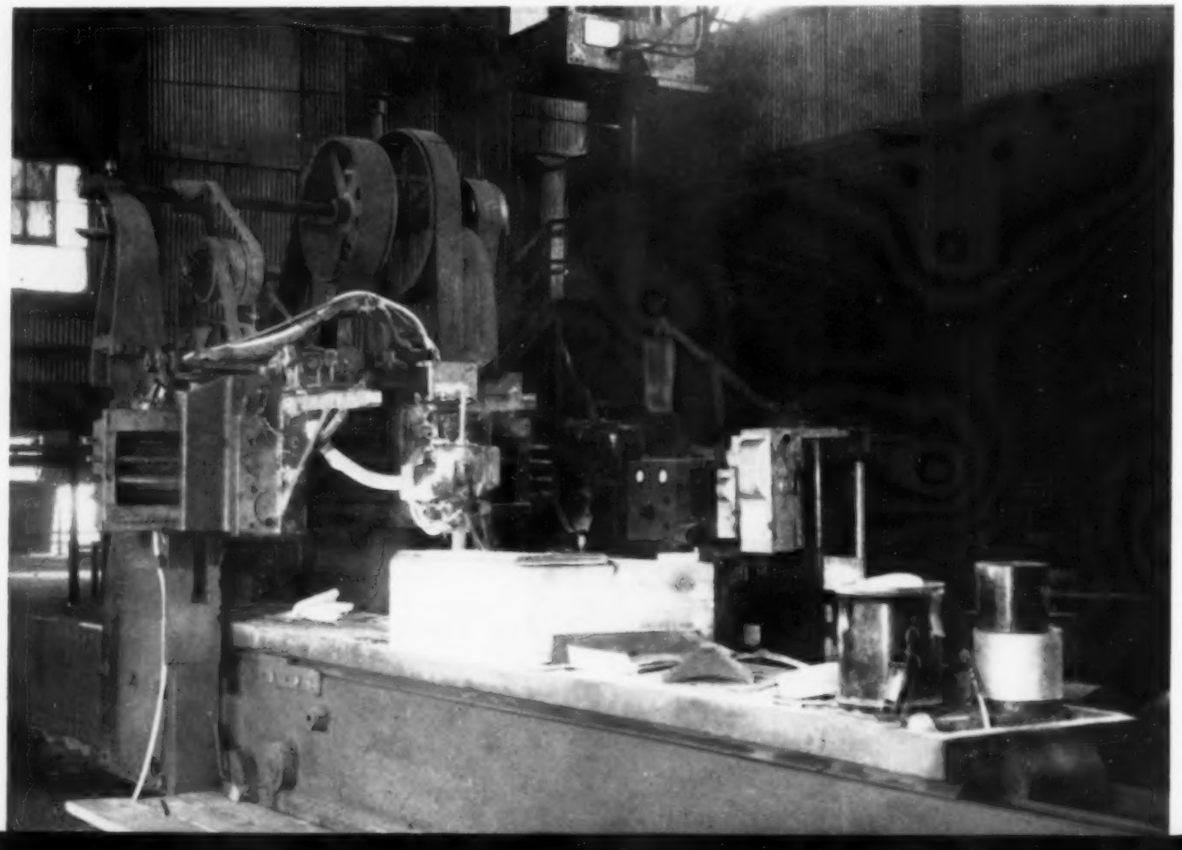
Adequate Bond Essential

When composite metals are to be fabricated, their usefulness is a function of the quality of the bond between the component parts of the composite. Unless the bond is perfect, the metals may separate in fabrication or use. Thus, electroplating alone is always done *after* the metal base has been rolled and frequently after the article has been formed, assembled, and all of the cold work completed on it. The reason is that the bond is weak — one of adhesion, not cohesion as in a weld. To get cohesion between the two elements in a plated composite it must be hot rolled.

A further necessity is that the composite have a uniform and entirely complete bond between the components. Thus, even though 98% of the area of contact between the components is perfectly bonded by cohesion, but the remaining 2% of area is held only by adhesion, the composite will be commercially unacceptable for many applications. Failure by buckling may be expected to occur when the composite is formed so the surface component is placed in compression, or the defects may show up as raised "blisters" when the composite material is heated, either completely or locally.

The requirement that the bond in composite metals be good for 100% the area of contact is the first and most important necessity. The second need is that the composite shall be made by low cost methods so that its manufacture and sale may yield a profit to the maker. This requirement immediately indicates that the metal should be operated on as early in the basic manufacture as possible. Steel is made, rolled and processed by the most expensive machinery in order to handle it on a mass production basis and produce it at a cost which promotes its universal use. The conclusion cannot be escaped that the time to make the

Experimental Equipment Included a Planer Whose Bed Carried a Preheating Furnace and Whose Tool Carriage the Welding Head and Traversing Device



composite is while the metal is in the ingot, slab, or in some cases the billet. If the metal is made composite here, it goes through all of the subsequent rolling and processing equipment in the steel mill which can handle it at high speeds and low costs.

The two contrasting cases of making nickel-clad steel and electroplating copper on steel, later to be hot rolled, illustrate the argument.

Nickel-clad steel is made by rolling together solid nickel slabs and steel slabs; a 1-in. thick nickel slab may be rolled onto a 9-in. thick steel slab. Thus, by working on 1 sq.ft. of steel 10 in. thick, 80 sq.ft. of nickel-clad steel is obtained when it is rolled down to ⅛-in. thickness.

In this thin plate, 10% of the thickness is nickel. Compare the ease of the indicated operation with the problem of electroplating 0.013 in. of copper on 0.125-in. thick steel for subsequent reduction 10% by hot rolling; it would be entirely prohibitive in relative cost, because 80 times the area of the composite nickel-steel slab would have to be operated on.

In the steel making process, the metal in the ingot stage represents the lowest cost of the metal in the solid state. Value is added by all of the subsequent operations. It is most desirable, therefore, to make the composite when the metal is in the ingot stage. Considering a rectangular ingot of low carbon steel, all that is needed to make it a composite is to add the necessary alloying elements to the metal on the required surfaces to get the desired chemical analysis. This may be readily accomplished by carbon-arc welding. It would be a roundabout and relatively expensive process to coat the surface of the ingot with the alloy desired in the form of a metal wire or rod and using the metal-arc welding process. Thus, to make by carbon-arc welding a composite having an 18-8 stainless surface, it is only necessary to add ferrochrome and nickel costing about 8¢ per lb. of 18-8 produced. Making an 18-8 surface by depositing 18-8 rod and metal-arc welding would immediately involve a cost of 50¢ to 60¢ per lb. for the stainless steel rod. In the latter case, the alloy is made and reduced to rod form suitable for welding and heavy costs are involved. In the carbon-arc method under description, and on which patents are pending, the stainless steel is made directly on the ingot using the ingot metal itself as the base. In this process an adequate bond (weld) is simultaneously made.

ON a preheated slab or ingot of carbon steel is placed a shallow pan containing crushed alloys and slag-forming ingredients and the entire area traversed, automatically, by a carbon-arc welding head. A thin, sound layer of alloy is thus formed and simultaneously welded to the steel slab, and the composite is ready for the rolling mill, where it is further processed by conventional equipment.

Alloy Made in Place

Experimental production of composite metals by carbon-arc welding has been carried out over a period of two years. To avoid excessive cost of experimental apparatus, work has been done on slabs where the depth to which the surface alloying extended could be from ½ to 1 in. Large electrical apparatus would have been required on thick ingots for a 20% depth of surface alloy and such apparatus was not available.

Typical Data for 20% Cladding on 2-In. Slab

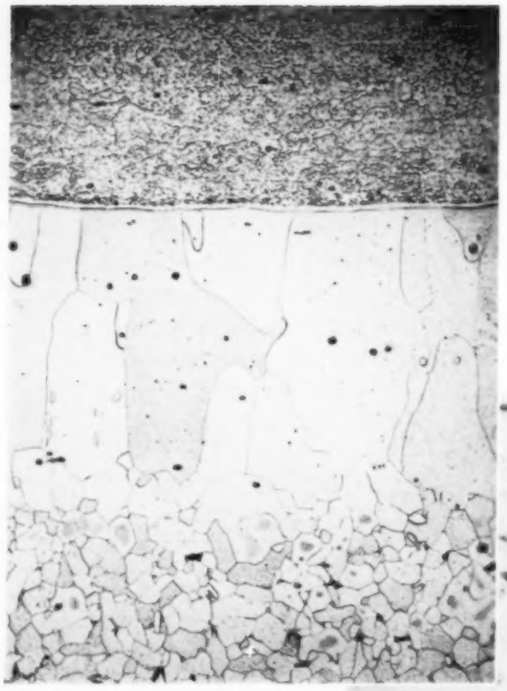
Alloy Type	Analysis of Surface					Operating Data			
	C	Cr	Ni	Mo	Mn	Preheat	Speed, In. Per Min.	Current, Amperes	Arc Voltage
18–8	0.08	17.52	8.52			800° C.	1.55	1800	44
	0.08	18.60	8.23			800° C.	1.61	1800	45
	0.06	18.36	8.92			800° C.	1.52	1800	49
	0.07	17.6	8.07			800° C.	1.53	1800	45
18–8	0.06	18.21	9.34	2.70	1.28	800° C.	1.55	1800	49
+ Mo	0.06	18.20	9.34	2.40	1.16	800° C.	1.51	1800	49
	0.07	19.86	10.68	3.10	1.38	800° C.	1.52	1800	45
	0.08	19.22	9.41	2.60	1.90	800° C.	1.50	1800	45
12 Cr	0.09	11.97				800° C.	1.6	1800	43
	0.08	12.59				800° C.	1.6	1800	42
17 Cr	0.09	18.33				800° C.	1.71	1800	44
	0.06	17.28				800° C.	1.7	1800	45
26 Cr	0.12	25.08				800° C.	1.68	1800	45
	0.09	29.6				800° C.	1.71	1800	44

The experimental equipment is shown in the first halftone (page 136). A "Tornado" carbon-arc head manufactured by Lincoln Electric Co. is mounted on the tool carriage of a planer. A motor and cam arrangement oscillates the head transversely to the bed. This cam was designed empirically to distribute the heat uniformly so that uniform depth of penetration of alloy into the base metal was the result. The cam turned out to be asymmetric due to factors which could not be calculated. Many composite slabs were sectioned, the penetration measured and the cam corrected accordingly. Current for the arc circuit was obtained from a Lincoln S.A.E. 800-ampere welder for thin alloy surfaces, and from a special motor-generator for those currents, up to 3000 amperes, necessary for thick alloy surfaces.

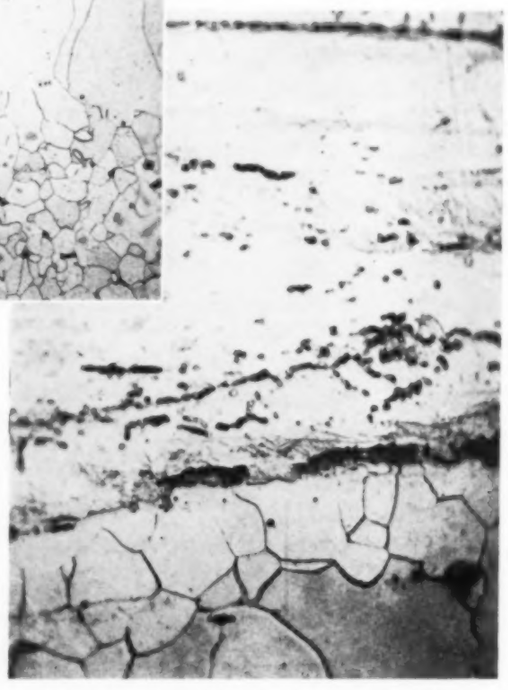
The view shows a furnace mounted on the planer bed. This is to preheat the slab and keep it hot while the arc is working on it. Adjustable speed is provided on the planer bed.

The operation for this experimental manufacture of composite metals may be briefly described in the following words:

The slab (0.04% to 0.06% carbon steel with 0.20% to 0.30% manganese) is put in the furnace and suitable ground connection made. The alloy is furnished in shallow pans. These pans are made of very thin, low carbon steel sheet and are melted in the process. Strewn on the bottom of the pan is the correct amount of alloy. In the making of 18-8, low carbon ferrochrome broken to 10 mesh is used, together with nickel shot. Molybdenum, columbium, manganese may be added, depending on the grade of alloy wanted. The pan is then completely filled with crushed slag, the height of the pan being designed so that when level full the right amount is present. This slag is composed of waste slag from an electric furnace in which 18-8 has been made, together with sand and calcium fluoride. The slab is now heated in the furnace with the alloy and slag in the proper location. An excess of slag is applied around the margin of the pans to keep the metal from flowing off the slab when the operation is in progress.



Completely Processed 14-Gage Sheet Clad With 17% Chromium-Iron Alloy. (All micros with electrolytic chromic acid etch and 5% nital. This one is photographed at 100 diameters.) Grain growth of low carbon steel backing in this sample is rarely seen and represents an incorrect heating cycle in the process anneal



Partly Rolled 18-8 Clad Steel, at 750 Diameters, Showing in Greater Detail the Structure Where the Metals Join

The slab is heated, with the top of the furnace covered, to a temperature of about 1500° F. as determined by pyrometer. Welding is started after the cover has been partially removed and proceeds from one end of the alloyed surface to the other. A 6-in. oscillation of the arc and 20-in. travel was found suitable for obtaining the specimens required for testing the composite material throughout the complete rolling, processing and final testing. On 2-in. thick slabs 1800 amperes, 45 to 50 volts across the arc, 1.6 in. per min. planer bed travel were

found suitable. Under these conditions, the metal alloyed would stay molten from three-quarters to the total length of travel, depending on the alloy being made. This was found to be a very important matter. After sectioning many alloyed slabs, it was shown conclusively that no failure of obtaining a perfect bond, over 100% of the area of contact, was ever encountered without striking evidence being visible on the surface.

Thus the process was developed to the point at which there could never be any uncertainty relative to this most important consideration. Any unusual condition resulting in the presence of blow-holes or slag inclusions is immediately evident on the surface of the alloyed metal. This advantageous set of conditions would be predicted by anyone who had had experience with carbon-arc welding under the conditions which this alloying is done.

After the alloying operation, the slab is removed from the furnace and cooled. The slag is easily removed when the slab is cool. The subsequent operations in the making of the finished product occur about as follows:

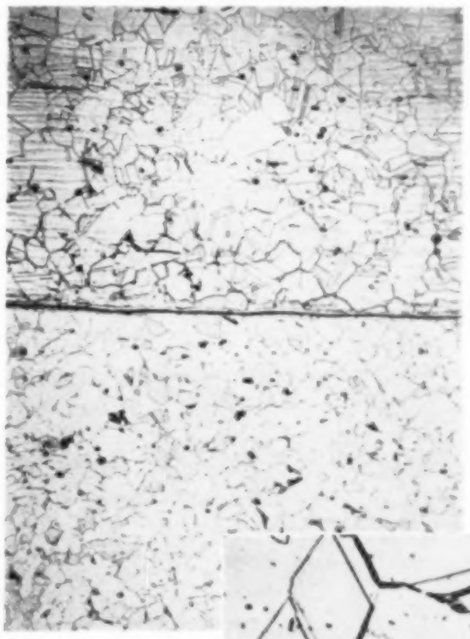
The surface of the alloy is given a light grind to remove scale and uneven spots. The slab is then heated preparatory to rolling. In the test slabs, cross rolling was first done to reduce and spread the alloy — the long dimension went into the rolls parallel to the axis of the rolls. Rolling was done in two stages, first down to about ½ in. thickness; the piece was then allowed to cool. Later the material was hot rolled on down to ⅜ in., ¼ in., or 11 gage (0.078 in.) The material was then annealed and pickled, and in some cases cold reduced down as low as 20 gage (0.037 in.).

No serious difficulty was encountered in rolling. Some special handling is required on account of the unavoidable tendency to curl due to difference in contraction coefficient of the two metals forming the composite.

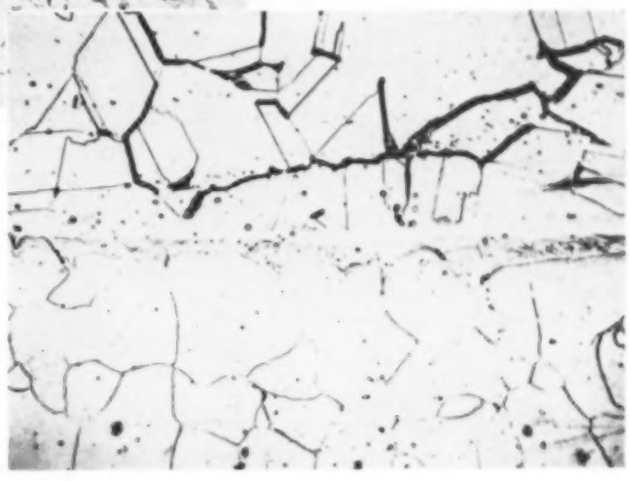
The table on page 137 gives typical chemical analysis of the alloy component of the composites made by the methods described. It is fairly obvious that the process is controllable to produce alloys in the form of composites within predetermined specifications. While the experimental apparatus was crude and difficult to control, every cause of variation was explored and the difficulties corrected in the design of commercial equipment.

Reproduced herewith are photomicrographs showing the nature of the bond between low carbon steel and the stainless alloy, as well as the condition of the latter. The most desirable physical contour of the bond is one that does not occur in a smooth plane. An apt analogy is the case of two optical flats wrung together. They cannot easily be separated by tension normal to the bonded surfaces, but may be slipped apart. The non-planar bond in this composite metal is entirely free from this defect of bonding. The illustration showing the presumably martensitic structure in a very thin

Completely Processed 18-8 Clad Steel, 14-Gage Sheets. Structure of low carbon base metal is normal. 100 diameters



Same Joint, Magnified 500 Diameters. The darkly etching grain boundaries in the 18-8 (above joint) indicate considerable carbide precipitation near this region



layer at the bond is characteristic of the process. That this layer does not affect the physical behavior is shown by the bent and severely deformed material in the view below.

Many tests have been carried out in an attempt to break the composite metals apart in the bond. None has been successful. The most severe is the "blister test", where local heat is applied to the stainless side with an oxy-acetylene blow pipe. The slightest defect in bond will result in a blister where the metal is heated. No such defects have been found.

The reason for this perfect score is simple. Had something gone wrong in the alloying operation, it would have been immediately discovered and the defect repaired by metal-arc welding, using a stainless rod, before the metal was rolled. There are no defects in the rolled metal for the reason that it would not have been rolled had there been any. Further, in the case of 18-8, the martensitic structure in the bond is stronger than either the normal stainless or the carbon steel; it would not be expected that the stronger metal would break before the weaker.

Cost and Adaptability

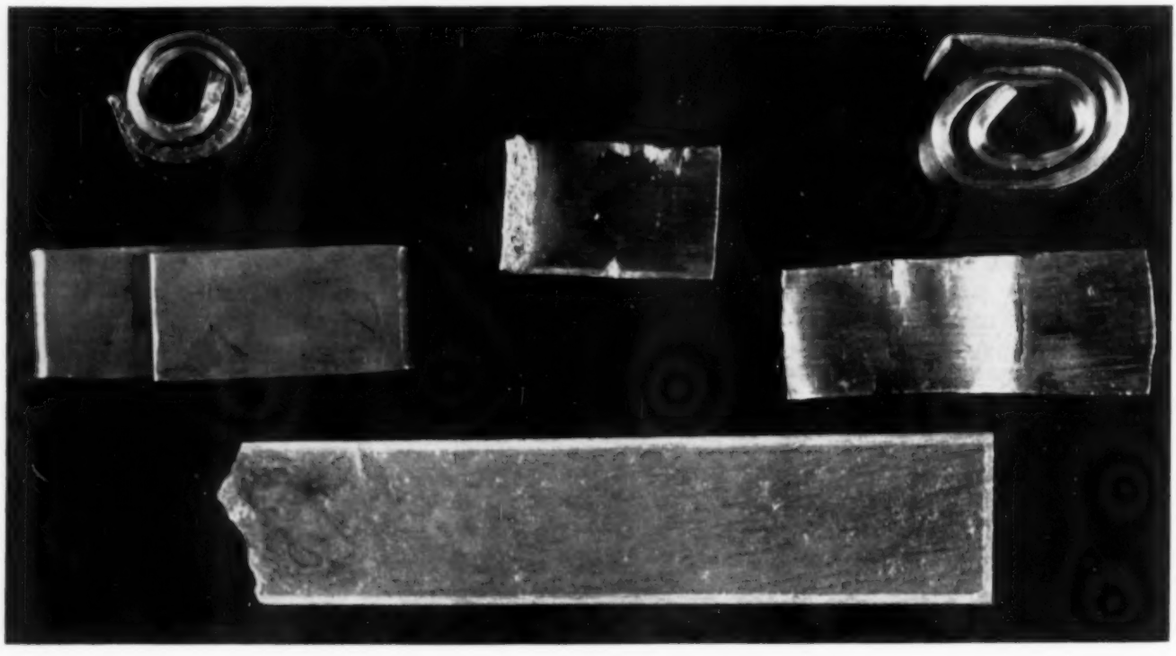
The factors which comprise the total cost of making composite metal by this method are ones with which steel mills are accustomed to deal so that cost of the product may be easily calculated. Thus, the alloy cost for the 18% chromium, 8% nickel metal is roughly 8¢ per lb. One 2500-ampere carbon-arc will make about 2½ lb. per min. of the alloy on the surface of a preheated slab. The power taken from the line is about 1.2 kw-hr. per lb. of alloy made. Carbon electrodes, slag, and other incidentals are almost negligible. Cost of preheating slabs may vary from $2 to $5 per ton. The cost of making the alloy on the surface of the slab is approximately 15¢ per pound for 18% chromium, 8% nickel (ordinarily the most expensive of the common stainless alloys).

The out-of-pocket cost of material, heat, power and labor to obtain a 20% cladding of 18-8 on low carbon steel, including the cost of hot rolling, is therefore on the order of $104 per ton of composite.

For costs of processing the composite beyond hot rolling a great deal depends on what is required. Pickling, grit blasting, cold reduction, polishing or other operations may be carried out at usual costs for these operations, known to those now making stainless sheet.

Since both the thickness of the slab worked on and the thickness of the alloy applied may be varied, the process is adaptable to composite metals by modern cold reduction having a very thin coating of alloy on one or both sides.

Samples of Composite Metal, Showing Heavy Deformation Endured Without Failure. Base metal in lowest sample has been removed by acid, to show non-planar character of bond on under side of cladding



HARDNESS OF STEEL

as affected by the quench

By Robert S. Archer
Chief Metallurgist
Chicago District
Republic Steel Corp.

PAPERS constituting the Symposium on Hardenability of the 1938 American Society for Metals' Convention were of impressive quality and value. Instead of reviewing these papers in sequence, we will attempt to present the material arranged by topics. It was with the hope of paving the way for this presentation that the rather long introduction, which is far from being a complete review of the previous status of the subject, was offered in last month's METAL PROGRESS.

Critical Cooling Rate

Most investigators agree that the critical cooling rate of a steel would be perhaps the best measure of its hardenability, but that the experimental determination of this rate is too much of a task for common use. "Critical cooling rate" is the minimum rate which will cause the complete decomposition of austenite into martensite. More exact definition is required, however, in respect to (1) the range of temperature over which this rate is to be taken, and (2) the basis for concluding that the minimum or "critical" rate has been determined.

Prior to the work of Bain and his associates on the "Transformation of Austenite at Constant Subcritical Temperatures" (*Transactions* A.I.M.E., 1930, v. 90, p. 117) it was common (H. J. French, for example) to determine the critical cooling rate at about 1300° F. Bain's work showed a maximum rate of transformation at about 1000° F. This led some investigators (among others Jominy, IV*, and Morris and McQuaid, III) to consider that the critical rate should be measured from about 1100° to 900° F. Grossmann, Asimow and Urban (II) concluded, however, that the "incubation time" beginning at about 1300° F. is also important in determining the penetration of hardness. They used the "half-temperature time" as the significant period, that is, the time required to cool from the quenching temperature to a point half way between this temperature and that of the cooling medium. Grossmann was not determining critical cooling rates directly, but this conclusion regarding the significant temperature range during quenching may also apply to the determination of critical cooling rates.

It is easy to say that the critical cooling rate is that which will "just prevent" the decomposition of austenite to products other than martensite, but no method is yet known for determining this rate without allowing *some* decomposition of austenite to troostite to take place. Digges used as a criterion the formation of 3% of nodular troostite in his study of the "Effect of Carbon on the Hardenability of High Purity Iron-Carbon Alloys" (*Transactions*

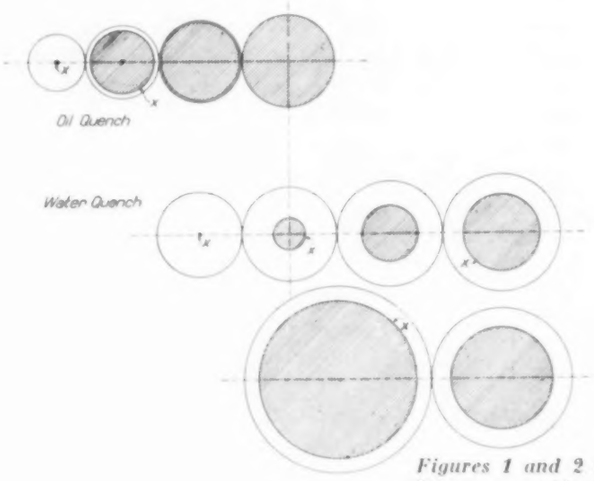
*Roman numerals refer to the contributions to the symposium, listed on page 145.

, 1938, p. 408). Burns and Riegel (VIII) took a drop of 3 points Rockwell C below the maximum value as evidence that hardening is no longer complete.

In discussion of Grossmann's paper, Dr. Sauveur objected to the recent practice of some writers of applying the terms "pearlite" or "fine pearlite" to the dark-etching, rounded constituent associated with martensite when hardening is incomplete. This constituent is referred to by others as "troostite" or, to distinguish it from products formed by tempering, as "nodular troostite" or "primary troostite". The present review is no place to discuss nomenclature, so "troostite" will be used, since Dr. Sauveur indicated that his recent questionnaire showed this to be in accordance with majority preference.

"Critical Size"

G. V. Luerssen (IX) points out the necessity of closely controlling hardenability and quenching practice in dealing with "light sections" of carbon toolsteel. He regards such sections as "critical" because a small change in the steel or the quenching will cause a large change in practical results, including such factors as surface hardness, toughness, quench-cracking, and dimensional changes.



Figures 1 and 2 From Paper II, a Diagrammatic Representation of Etched Cross-Sections of Quenched S.A.E. 3140 Bars, and "Characteristic Curves" Drawn From Same

This is closely allied to Grossmann's conception of critical size as a criterion of hardenability. His critical size is the diameter of a round bar which will just "harden through" on quenching, as judged by the disappearance of the soft core shown by etching a transverse section. This does not mean that the section is full hard clear through, for Grossmann and others show that the line of demarcation between the hardened rim and the core occurs where the structure is half martensite and half troostite and where the Rockwell values are substantially below the maximum.

In the symposium papers by Grossmann and his associates (II) and by Queneau and Mayo (VII) it is proposed to determine critical size by extrapolation, but the bases for extrapolation are somewhat different.

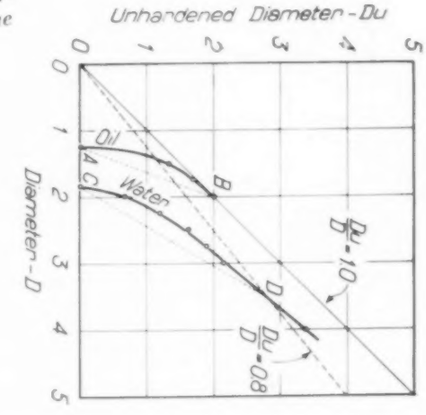
Quenching Rate in Testing

It is well recognized that the hardness distribution in a quenched piece depends both upon the hardenability of the steel and upon the quenching practice. In most of the hardenability testing the attempt has been to standardize a quenching procedure and to describe it in such detail that it can be duplicated by others. This is the basis, for example, of the tests used by Jominy (IV) and by Burns and Riegel (VIII). Jominy quenches a round bar in a fixture on one end only and has measured the cooling rates at various distances from this end.

Grossmann (II) apparently considered the standardization of quenching too difficult and proceeded to develop methods of determining hardenability in which the actual quenching rate can be deduced from the examination of the hardened specimens.

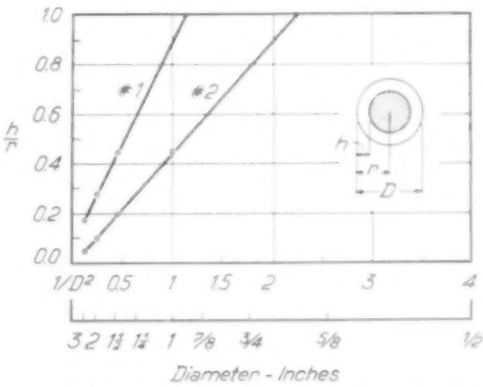
Deducing the Quenching Rate

This is perhaps the most important contribution of the paper by Grossmann, Asimow and Urban (II) and is based upon their observation: "The rate of change of the depth of hardening, as the bar size is increased, is characteristic of the severity of the quench". The principle may be illustrated by reference to Fig. 1



and 2 of their paper, reproduced at the bottom of the preceding page. In Fig. 2 the diameter of unhardened core *(Du)* is plotted against the diameter *(D)* of round bars of the same steel quenched in oil and in water. Two curves are obtained, one "characteristic" of the oil quench and the other of the water quench, and indicate the severity of the quench, which is measured by the "heat transfer equivalent" *(H)*. Now it is possible that a given "characteristic" curve may be duplicated as to *form* with a different severity of quench applied to a steel of different hardenability. This will occur with equal values of the quantity $H \cdot D$, that is, the heat transfer equivalent times the bar diameter. Such curves will, however, differ in dimensions, because of the different bar diameters involved. By matching characteristic curves both as to form and dimensions, it is possible to determine the heat transfer equivalent *(H)* of any quenching process applied to a steel of any hardenability, providing measurements of unhardened cores of various bar diameters of it are available.

The paper under discussion includes numerous charts to be used in the application of this principle. These have been verified to some extent by actual experiments, but are based chiefly on mathematical calculations of a rather extensive and laborious nature based on laws of cooling and on certain assumptions, similar to those previously employed by Howard Scott in his discussion of "Some Problems of Quenching Steel Cylinders" in *Transactions* ⚙, 1934, p. 68. Objections may be raised to these assumptions on theoretical grounds, and to the validity of all the calculations thus questioned. The proof of the pudding will be in the eating, and it is to be hoped that sufficient experimental work can be done to verify the charts, or to show any limitations that may exist.



Apparent Change in Hardenability of 1050 With Change in Quenching Medium (No. 1 Is Water, No. 2 Is Oil). Fig. 8 of Paper VII

Hardened Rim Versus Bar Diameter

Closely related to the above work is that reported by Queneau and Mayo (VII). Their Fig. 8 shows their "hardenability lines" for an S.A.E. 1050 steel quenched in water and in oil. Like Grossmann, they quenched bars of various diameters and measured the penetration of hardening as shown by etched cross-sections, but their method of plotting is somewhat different, so that the lines in the two papers cannot easily be compared. They plot $h \cdot r$ against $1/D^2$, where h is the depth of the hardened rim, r the radius of the bar, and D the diameter of the bar. Mayo had previously pointed out that this gives a straight line, at least in some cases. Queneau and Mayo say that the greater part of their curve should "closely approximate a straight line" on the basis of the previously mentioned mathematical treatment by Scott. How close this approximation is, and how far the straight line may be extrapolated beyond points determined by experiment, is the important question.

Even though the methods of plotting may be different, Grossmann's curves and Mayo's straight lines cannot both be correct. Strangely enough, the authors of both papers appear to have followed Scott's calculations. Scott was very helpful in this matter by presenting a discussion in which he included curves plotted in their manner, but calculated on the basis previously employed by him and later by Grossmann, Asimow and Urban. Scott's calculated curves agreed with the experimental ones of Queneau and Mayo in having portions which were substantially a straight line, but they curved markedly at each end. It is easily seen that the lines must curve at their lower ends, since they must finally point closely toward the origin, but this is not very important, because it involves very large bar diameters. Really the important end of the line is the upper one, because it is by extrapolation to $h/r = 1.0$ that Queneau and Mayo propose to determine the "critical size" of Grossmann, that is, the bar diameter which will just harden through (as shown by etching). Scott's calculations, and some experimental results, indicate that extrapolation as a straight line is not always justified.

Now we all like straight lines better than curves (at least in mathematical matters) and

for this reason the relationship discussed by Queneau and Mayo offers further attractive possibilities. The straight line seems to be valid, at least for certain steels in certain sizes. Probably the largest bar to which it is applicable should still have a completely hardened rim of substantial thickness, while the smallest size should not come too close to being hardened clear through. It would then seem that the slope and position of the straight line portion of the "curve" could be used as a measure of the severity of the quench. The treatment of these straight lines would perhaps be more simple than that of Grossmann's curves. No doubt further experimental work will be done which will more fully define these relationships.

Ideal Quench

The various measures of hardenability such as Grossmann's critical diameter (II), or the distance from the water-cooled end in Jominy's test (IV) or the area under the hardenability curve of Burns and Riegel (VIII), have definite values only when related to specific quenching conditions. Grossmann shows how the critical diameter obtained under any definite set of actual quenching conditions can be translated into the hypothetical critical diameter for an "ideal quench", providing we assume the validity of his calculated cooling relationships. The ideal quench is one in which the surface of the steel is instantly lowered to that of the quenching medium. The cooling of the interior of the steel is then limited only by thermal diffusion through the steel. This is the fastest possible quench, for which the heat transfer equivalent *H* is infinite, and is actually approached when water quenching clean surfaces with vigorous agitation or high pressure.

Reproducibility of Quench

Luerssen (IX) very properly points out that "most uniform hardening will result by so regulating conditions as to obtain the most drastic quench possible from the particular medium employed, involving agitation and correctly directed flushing". This applies to hardenability test specimens as well as to commercial parts or tools.

The schemes of Grossmann and of Queneau and Mayo depend upon reproducing the severity of quench on the same steel in round specimens of different diameters. It is probably not as easy as one might suppose to maintain a fixed value of the heat transfer equivalent *H* when dealing with these various sizes, and any unintentional variation would result in variations from the calculated curves. This would be especially likely to occur when the severity of the quench is mild for the quenching medium employed.

The Hardenability Specimen

It was shown by Burns, Moore and Archer in their discussion on "Quantitative Hardenability" in *Transactions* ASM, 1938, p. 1, that the experimental error in hardenability testing can be reduced to a fraction of the variation in hardenability which may result from normal chemical segregation within a single ingot. In precision testing it is therefore important to consider the analysis of the specimen rather than the heat analysis, and even the transverse segregation within the specimen itself may have a substantial effect on the results.

FOLLOWING his paper in last month's issue, describing the development of a concept of hardenability, Mr. Archer now analyzes various papers in the ASM Symposium on Hardenability to show the diverse ideas held about the experimental determinations to be made so that the essential information to characterize each steel may be readily acquired.

The methods of Grossmann and of Queneau and Mayo depend not only on reproducing the quench but also on using the *same* steel in the different sizes. Consideration must therefore be given to transverse segregation to make sure that the various bars really represent the same hardenability. If the various specimens are taken adjacent to each other, longitudinal segregation should not be bothersome.

When Jominy's test is applied to carburized specimens, the question of transverse segregation becomes one of carburizing practice, since any transverse segregation originally present (chiefly with regard to carbon) is probably offset by carburizing. When, however, this test is

Papers in the Symposium

I. Physics of Hardenability, by Robert F. Mehl
II. Hardenability, Its Relation to Quenching, by M. A. Grossmann, M. Asimow and S. F. Urban
III. Effect of the Silicon and Aluminum Addition, by M. J. R. Morris and H. W. McQuaid
IV. Hardenability Tests, by Walter E. Jominy
V. Hardenability of Low Chromium Steels, by Walter Crafts and John L. Lamont
VI. Transverse Hardness Tests, by Gordon T. Williams
VII. The Hardenability Line, by B. R. Queneau and W. H. Mayo
VIII. Hardenability of Plain Carbon Steels, by John L. Burns and Glen C. Riegel
IX. Hardenability in Light Sections, by G. V. Luerssen

applied to uncarburized steels, it is to be kept in mind that the steel under test is the outer zone of the specimen where the Rockwell impressions are made.

Prior Structure

It is well known that the prior treatment and structure of a steel may affect the results obtained in hardening. It has been somewhat confusing that the same type of prior treatment is apt to have one effect on a hypo-eutectoid steel and the opposite effect on a hyper-eutectoid steel. This matter is nicely clarified by G. V. Luerssen (IX): "Normalizing results in a finer distribution of carbide, easier and more complete solubility in heating for quenching, and consequently deeper penetration — provided, as pointed out by Foley, that the quenching temperature is high enough to absorb all carbide. This condition prevails on steels up to the eutectoid composition. However, on hyper-eutectoid steels it is not the practice to heat for quenching over the A_{cm} line, but rather to a considerably lower temperature where appreciable carbide remains out of solution. In these steels the size and character of these excess carbides have a marked influence on hardenability. If the steel has been thoroughly spheroidized before heating for quenching, the carbides appear to have little effect, and hardenability is of much the same order as a eutectoid steel of otherwise the same composition. However, if the carbides are extremely fine, as those resulting from a previous oil quench, they tend to increase the critical cooling velocity by acting as nuclei for pearlite transformation, and consequently shallower hardening."

A few years ago McQuaid postulated that in some steels the carbides dissolve very slowly at temperatures even above the upper critical and thereby act as grain growth inhibitors. (See his papers in *Transactions* ASM, 1935, p. 832, and 1937, p. 499.) Similar views have been expressed by others, especially with reference to carbides spheroidized by long treatments below the critical. The work reported by Lauderdale and Harder at the 1938 ASM Convention was designed to test such hypotheses.

In their "Study of Carbide Solution in Hypo-Eutectoid Plain Carbon and Low Alloy Commercial Steels", the latter authors spheroidized various steels by holding for 111 to 150 hr. at 1300 to 1325° F. In steels up to about 0.40% carbon, they report very rapid solution of carbides at temperatures above the critical, and feel that this precludes the possibility that carbides in such steels can inhibit the coarsening of the austenite grains. In two steels of 0.77 and 0.78% carbon, the time required for enough carbon to go into solution to develop full Rockwell C numbers was quite short. These holding times left undissolved carbides, and longer times were required for their complete solution. They conclude that carbide size and distribution are important factors in the behavior of steels during heating for hardening, but that the carbides in hypo-eutectoid steels do not play any significant part in preventing the growth of the austenite grain. Of the steels tested by the authors, five were plain carbon, two contained vanadium (0.18 and 0.22%), and two molybdenum (0.38 and 0.54%).

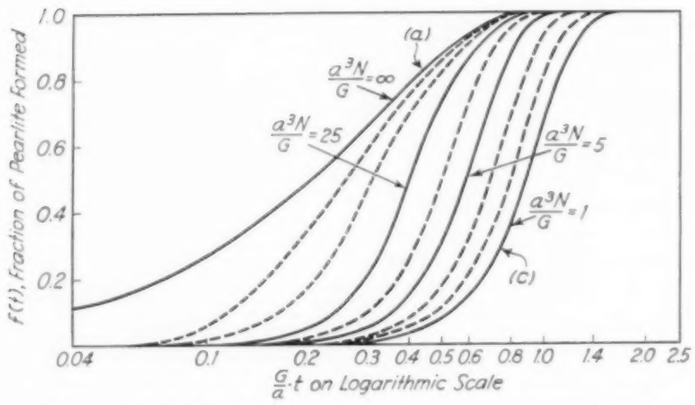
Measures of Hardenability

To summarize: Methods of expressing hardenability used in these recent papers include:

1. *Critical Cooling Rate*, taken by Digges as the rate from 1110 to 930° F. to produce martensite plus 3% of troostite.

2. *Critical Size*, the diameter of a round bar which will just "harden through" as judged by etching the cross-section. The center is actually half martensite and half troostite. Grossmann calculates the critical size for the "ideal" or maximum possible quenching rate. Queneau and Mayo find the critical size (by extrapolation) for some definite quenching condition.

3. *Distance* in inches from water-quenched



Family of Calculated Master Curves for Isothermal Reaction Austenite → Pearlite. Fig. 6 of Mehl's paper (I). Computed on assumption that nodules of fine pearlite nucleate at austenite grain boundaries at rate N, grow as half spheroids by radial, fan-like extension at rate G, in austenite grains of mean radius a; time is t. Experiments, by Davenport and Bain (Transactions ASM, *1934, p. 894) on 1.17% C steel coarsened to various sizes of austenitic grain, match one such calculated curve almost exactly, indicating that assumptions are correct*

end of specimen to point where Rockwell C value drops below a chosen specified value in Jominy's test with fixed quenching conditions.

4. *Area Under "U" Curve,* the "area" in "Rockwell-inches" under the curve formed by plotting Rockwell C values against distances across a one-inch diameter round. Fixed quenching conditions. Used by Burns and Riegel (VIII). More complete "S-A-C" rating includes surface Rockwell, area, and center Rockwell C values.

Critical Size Vs. Cooling Rate

It is to be noted that the cooling rate which results in 50% martensite plus 50% troostite (material which etches readily on a cross-section) is much slower than the critical cooling rate of Digges which results in only 3% troostite. Furthermore, these two rates are not necessarily proportional in two different steels.

R. F. Mehl (I) presents an interesting and extensive analysis of the isothermal reaction rate curve, as determined experimentally by Bain. Both the actual data and Mehl's theoretical conclusions indicate that the *form* of this curve varies in different steels. It thus seems quite possible to have two steels *A* and *B* such that *A* will form 3% of troostite at a given temperature more quickly than *B*, but require longer to form 50% troostite. Steel *A* would thus have a higher critical cooling rate (indicating lower hardenability) but a larger "critical size" (indicating higher hardenability).

Such important aspects of the problem as the effect of chemical analysis of the steel, the mechanism of transformation of austenite to martensite, and the application of all these things to every-day production problems must be reserved for next month's issue.

DESULPHURIZING IRON WITH CARBIDE

From 1938 Annual Report of U. S. Bureau of Mines

THE PRACTICE of desulphurizing molten pig iron through the use of sodium carbonate or of mixtures in which sodium carbonate is the active reagent has been revived in recent years, especially in European countries where it is the basis of important new furnace operations. As the allowable limit of sulphur in hot metal for the openhearth furnace is more carefully controlled, the use of supplementary methods of desulphurization in the blast furnace ladle or hot metal mixer is becoming more attractive. Experiments recently completed indicate that by the proper application of calcium carbide it may also be used to supplement the desulphurization obtained in the blast furnace, and that the sulphur content of molten pig iron may be reduced rapidly to a value approaching 0.01%.

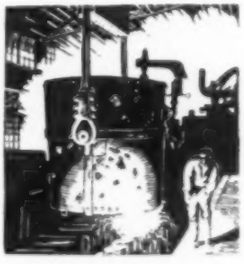
The method of treating the hot metal was found to be important. To obtain efficient utilization of carbide it should be mixed with a suitable flux and allowed to react below the surface of the metal bath. Sodium chloride was found to be as efficient as any flux tried (including calcium fluoride, calcium chloride and sodium fluoride) and has the additional advantage of being comparatively inexpensive. In laboratory experiments, the mixtures of calcium carbide and flux were pressed into briquets and immersed in the hot metal by means of a graphite and iron pipe holder. In plant practice a suitable holder might be used, or a layer of the mixture might be rammed into the bottom of a *(Continued on page 180)*

SOLIDIFICATION OF RIMMING STEEL INGOTS

Reviewed for Metal Progress by
John Chipman
Professor of Metallurgy
Massachusetts Institute of Technology

ORGANIZED WORK on steel ingots has been in progress in England since 1924 and the interim reports published by the Iron and Steel Institute approach 2000 pages in total. While we have had nothing on this side to compare with this, some special problems concerning pit practice have been intently studied by certain American steel companies. To this great mass of information now comes a report of an investigation on the solidification of rimming steel ingots which was begun in 1934 by a committee of Jernkontoret (The Swedish Ironmasters' Association). This paper was presented at the fall meeting of the A. I. M. E., written by Professors Hultgren and Phragmén of Stockholm and ably presented by the former. It appears destined to take its place among the classics of metallurgical research.

A careful review of the literature on rimming ingots and ingot gases brought to light some interesting historical information. One of the pioneers in this field, F. G. Müller, in 1879 found hydrogen in the blowholes of an ingot and concluded that the holes were caused by hydrogen. In spite of the very clear proof furnished by Bessemer that the gas evolved from liquid steel is mainly carbon monoxide, the hydrogen theory persisted for many years. At one time it was even developed into the fantastic idea that the rim holes were formed by hydrogen, the intermediate or deep-seated holes by carbon monoxide, and the irregularly distributed core holes by nitrogen or ammonia.

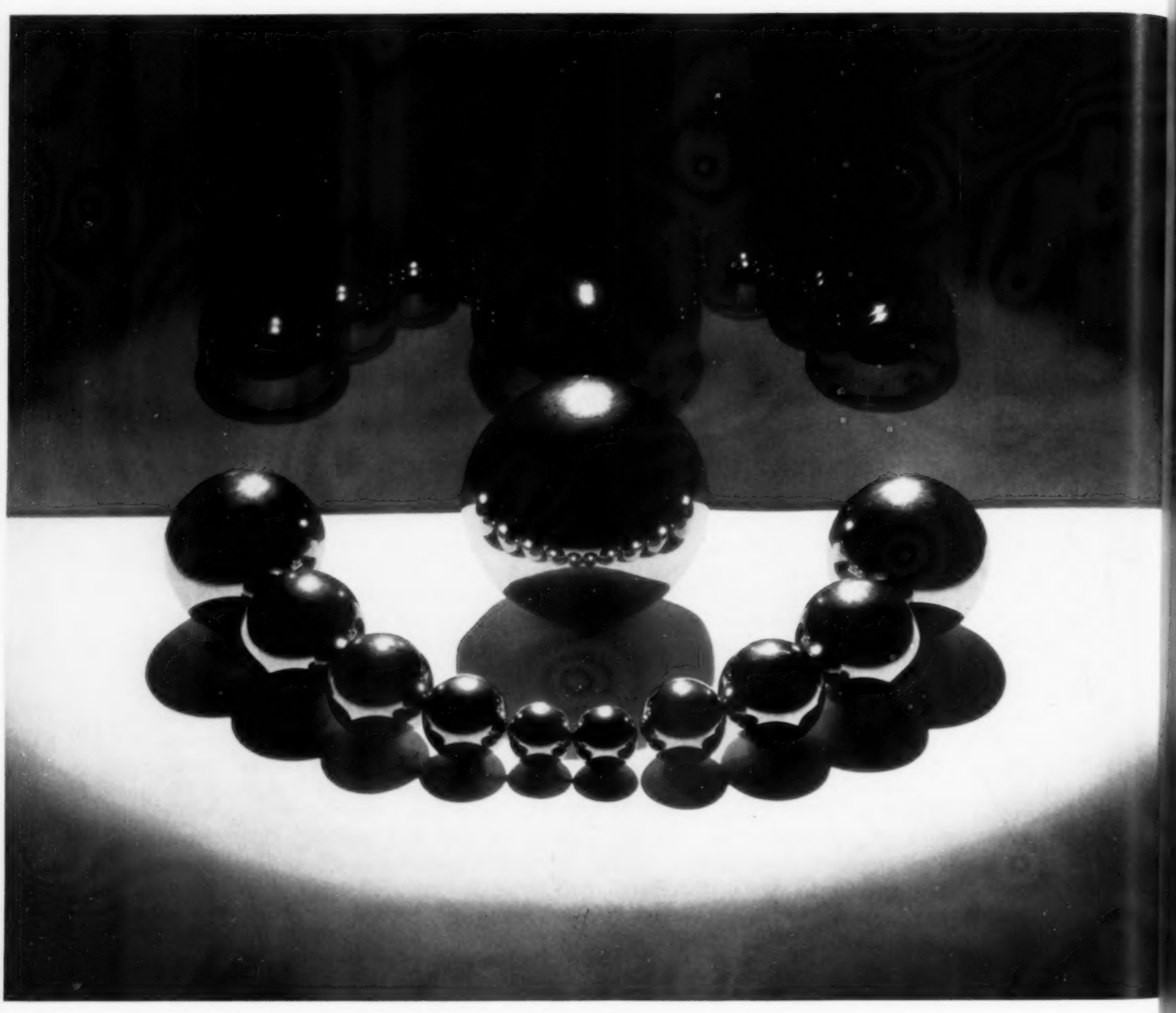


Early in the Swedish investigation a new technique was developed for studying the primary structure of low carbon steel. The true primary structure is ordinarily not observed in a sectioned ingot because of the development of a secondary structure during the slow cooling of the ingot through two transformation ranges and because of the inadequacy of ordinary etching methods for bringing out the fine details in the rim zone. In this study whole ingots or longitudinal sections cut from them were water quenched from 1800° F. and annealed at 1300° F. to yield a fine structure of ferrite with small rounded particles of cementite, and carefully polished sections were etched first in nital, then repeatedly in diluted Stead's reagent.

The structures found in the rim zone of the ingots included the usual "rim holes", the familiar elongated blowholes occurring in the lower half of the ingot. In addition a new structure was encountered which had not previously been described; curved lines appeared which quite obviously outlined the temporary contour of a blowhole, the gas content of which had been suddenly replaced by liquid metal. These "hole contour lines" were observed in the sound skin of 0.08% carbon steel ingots and in the nearly sound rim zone above the level of rim holes. Here also were "rim channels" or very small pores which appeared to locate larger holes that were nearly filled as soon as formed.

Thus it appears that the existence of a sound skin on a rimmed ingot, the phenomenon which makes rimming steel a commercial success, must be regarded from a different viewpoint than has heretofore been current. The production of a sound skin is not a question of how to solidify the shell without blowholes, but how to control its formation so that the blowholes which do form will be quickly and completely refilled.

Hultgren and Phragmén find that the structure of the core of a rimmed steel ingot consists mainly of globular primary crystals with scattered irregular blowholes and one or more large axial holes accompanied by patches of segregate. Sloping lines symmetrical to the axis suggest deformation *(Continued on page 188)*



Out-Mirroring a Mirror

An assemblage of burnished steel balls reflect each other — jewel-like — and the spot light better than does the mirror, placed to form the back wall. In such views the photographer is hard put to arrange the lighting so he and camera are not reflected in every ball.

Metal Progress; Page 148

BALLS FOR BEARINGS

are last word

in precision

By Hudson T. Morton
Chief Metallurgist
Hoover Ball & Bearing Co.
Ann Arbor, Mich.

MANY REFERENCES from ancient literature will indicate that leather balls were used in sport since time immemorial, and round stones are of course an ideal missile. Chinese writings indicated that that remarkable people not only knew about ball bearings but also had a method of manufacture, but this knowledge was closed to the outer world. The ball bearing as we know it today undoubtedly was one of the early by-products of the bicycle industry, even though patents were taken out in England and America as early as 1860. In 1868 an Englishman, E. A. Cowper, suggested the use of ball bearings as a method of reducing friction in bicycles, but did nothing toward using the idea.

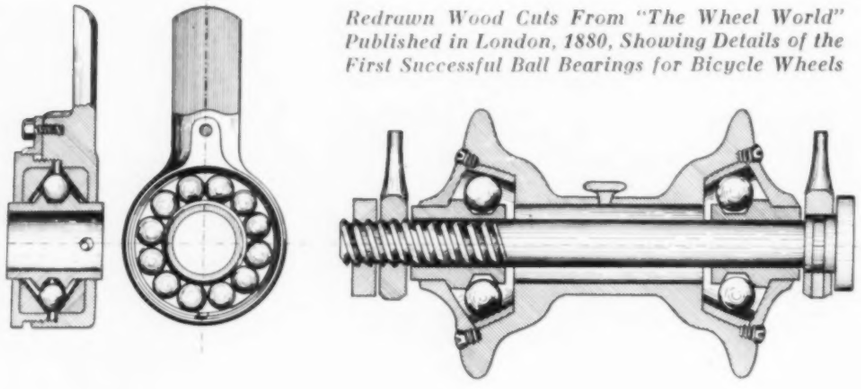
Files of *The Wheel World*, an English publication, indicate that William Bown of Birmingham was the first manufacturer of commercial ball bearings. His patents, taken out with J. H. Hughes in 1877 and 1880 caused a great deal of litigation, which he survived for several years. The drawing on page 150, reproduced from this old publication, shows the construction; the text indicates that the steel collar on the axle has a groove left on it, wherein 12 balls are placed. One of the outer cones is fixed in the housing, the other cone in the front bearing is adjustable. The text says: "The bearings, being made under Mr. Bown's own supervision, are finished in the most accurate manner, and no necessity exists for a distance to be ridden with stiff or jerky bearings so as to wear, *i.e., cut* them into shape. Every part is fitted to a hair's breadth" — quite a fine tolerance, it must be admitted. Singer & Co. of Coventry, at one time the largest producer of bicycles in England, had a standing order in 1880 with Wm. Bown for 20 ball bearings a day.

Balls and races were hand-made at this time under great secrecy. It is said that the parts were made of cast steel and machined to size and shape. As a result they were very expensive, and bicycles using them commanded an extra price of 30 shillings for this optional equipment. An important patent was granted to J. Harrington and H. Brent in 1879 covering hardened steel bushings on the inner shaft, fitted with grooves for the balls of a ball bearing. Thus we begin the use of hardened steel parts in ball bearings. W. Hillman later designed and erected a machine at Coventry for cutting balls from steel wire.

In 1880 besides William Bown of Birmingham, the following organizations were making ball bearings in England: Hillman, Herbert, and Cooper; A.B.C. Bearings; Palmer & Co., D. Rudge & Co.; and Singer & Co. Most of these firms were manufacturing bicycles at Coventry or Birmingham.

While these English companies were mak-

ing ball bearings under great secrecy by hand methods and not worrying about interchangeability of parts, Americans were busy designing and building machinery for production operations on balls. George F. Simonds of Fitchburg, Mass., developed, patented, and built a machine for making round forgings from steel bars and wire, and his Simonds Rolling Machine Co. made steel balls which were sold by the Ball Bearing Co. of Boston, Mass. Employees who left these firms organized the Fitchburg Steel Ball Co. which was later sold to the Cleveland Screw Machine Co. of Cleveland, Ohio, which also acquired the rights on Richardson's dry grinder and other ball making machinery scattered about the United States, most of which had been patented by John J. Grant. (In 1887 Mr. Richardson of the Waltham Emery Wheel Co. of Waltham, Mass., obtained the basic patents on a dry grinder for making ball forgings round.)



Redrawn Wood Cuts From "The Wheel World" Published in London, 1880, Showing Details of the First Successful Ball Bearings for Bicycle Wheels

So much for the origin of the American industry. Some notes on the German industry are instructive: "About 1890 the Cleveland Screw Machine Co. designed and built for the Deutsche Waffen und Munitions Fabriken, of Berlin, Germany, equipment used in its original steel ball plant and this marked a most important step in the trade owing to the reputation for making high-grade balls that was later acquired by this firm. The machines built and shipped to Germany had no reference to American manufacturing rights, and the Cleveland Machine Screw Co. continued to operate its plant in the usual way." Thus the German ball business was dependent upon American ingenuity for its start and the above mentioned company employs the trade mark "DWF" as a part of SKF Industries, Inc. (the American name for this large international organization).

In 1894 the consolidated bicycle manufacturers under the trade name of Pope Manufacturing Co. of Hartford, Conn., acquired the Cleveland Screw Machine Co. and moved its equipment to Hartford. During the subsequent depression the bicycle business declined and many cycle manufacturers and bearing makers had to close. In 1901 the Standard Roller Bearing Co. of Philadelphia was formed to acquire this scattered ball making equipment and has been in business ever since. This company later changed its name to Standard Steel & Bearings Co., moved to Plainville, Conn., and merged in 1923 to form a division of Marlin-Rockwell Corp. by which name it is now known. Connecticut was the heart of the bicycle business; New Departure, the bearing division of General Motors Corp., starting early in Bristol in the manufacture of axles and coaster brakes.

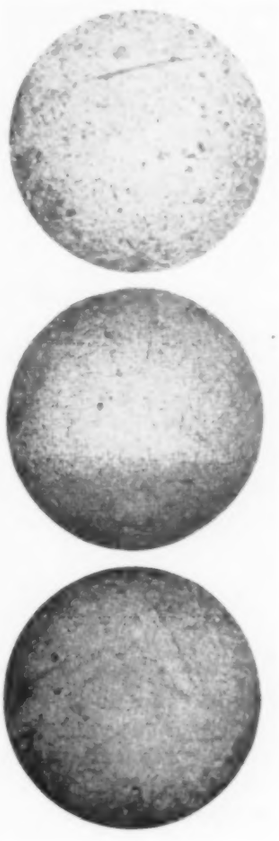
In 1906 L. J. Hoover left the Standard Roller Bearing Co. to form the Grant and Hoover Co. of Merchantsville, N. J., to manufacture high grade steel balls. His associate John J. Grant was the designer and patentee of most of the ball making machinery then in use in the United States, while Mr. Hoover was familiar with the sales and management features of the companies. This company continued in business for several years until purchased by Otto Schaum and associates and moved to the Schaum and Uhlinger Co. at Philadelphia. This firm is now the Fletcher Works, manufacturers of looms and hydro-extractors; the ball company was reorganized and called Atlas Ball Co. In 1918 SKF Industries, Inc., purchased most of its stock and continues to operate the Philadelphia plant under the old name for the production of high grade balls.

As to the formation of the writer's company, it occurred in 1913 when L. J. Hoover in collaboration with ten residents of Ann Arbor, Mich., formed the Hoover Steel Ball Co. Its early success was due to its high quality product during the War when balls could not be imported from Germany. By contracting with

machine tool builders for their entire output of ball-making machinery the Hoover Steel Ball Co. was able to expand rapidly even during the War. In 1924 the Imperial Bearing Co. of Detroit was acquired with its equipment for making tapered roller bearings. The present name, Hoover Ball & Bearing Co., is in keeping with the scope of present production.

Characteristics of a Good Ball

Thus far nothing has been said about the quality of steel balls. Tests run in 1885 by Professor Boys and published in *Proceedings* of the British Institution of Mechanical Engineers showed that the ball bearings of a bicycle wore rapidly during the first 500 miles of use and the oil became filled with fine steel particles while the races became grooved and had a high luster. After cleaning the balls and races the test was continued another 1400 miles, and less change of size or wear was found than during the first 500 miles. This indicated a probable variation of size and sphericity of the balls when they were first assembled, and that running conditions had lapped them to a condition much more round and uniform in size. This was very similar to the results obtained with the pistons, rings, and cylinders fitted in the early automobiles; purchasers were required to drive slowly for the first 500 miles, thoroughly clean all dirt out of the crank case and fill with fresh oil. Thereafter the automobile ran much better.



Unetched Surfaces of Balls Made in 1907 by Three Companies. Magnified 35 diameters (Henry Hess)

The use of automatic machinery in ball making has improved the quality and uniformity of balls surprisingly and they achieve tolerances unheard of in other industries. During the 19th century the advertising literature of ball manufacturers talked about balls within a tolerance of one thousandth of an inch or less. In 1907 Henry Hess of Hess-Bright Co. (later consolidated with other companies to become a part of SKF Industries, Inc.) published in *Transactions* of the American Society of Mechanical Engineers a translation of Professor Stribeck's paper covering the load ratings of ball bearings and in this connection gave his own comments derived from experience in the manufacture and use of ball bearings. At that time he wrote:

"The requirements of a good ball are:

"a. **Truth of shape and size.** The permissible limit of error will vary with the character of the material. In general, the better the latter, that is to say the smaller its deformation under a given load, the more accurate must the ball be. It is evident that, were a ball so much larger than its fellows as not to deform sufficiently under its share of the load to permit others to carry, it would then not only itself have to carry more than intended, but would also transmit more than intended to the supporting surfaces of the races. If, on the other hand, the ball were smaller than its mates, it would be underloaded or not loaded at all, and the others correspondingly overloaded. What has been said of variations in ball size, of course, applies similarly to variations from truth of outline. All requirements will be met if the balls are true to shape within 0.0001 in. and if all the balls used in each individual bearing have a similarly small error in size. It must not be inferred that for

Lowered Tolerances in Last 25 Years for Balls 2 In. and Under

Date	"Micro-Chrome"		"Standard"		"A-Grade"		"Hardware"	
	Sphericity	Size	Sphericity	Size	Sphericity	Size	Sphericity	Size
1915	0.0001	±0.0001	0.0002	±0.0002	0.001	±0.0005	No Guarantee	
1926	0.000025	±0.00005	0.0001	±0.0002	0.0002	±0.0005	0.001	±0.002
1931	0.000025	±0.00005	0.00005	±0.0001	0.0002	±0.00025	0.001	±0.002
1934	0.000025	±0.000025	0.00005	±0.00005	0.0002	±0.0002	0.001	±0.002

materials of lower grade, large inaccuracies are permissible.

"b. **Surface finish to a high degree is also essential.** What is usually considered a very good finish indeed may be characterized as totally inadequate. The recognition of grinding or polishing marks not only by the bare eye, but with an ordinary pocket reading lens condemns balls utterly; this is true of a bearing having long life under high loads and speeds. Oft repeated endurance runs under conditions where the finish was the only variable have abundantly proved this, at first unsuspected, fact. This was discovered while investigating an apparently inexplicable difference in lasting qualities. As life is too short for a try out under normal loads, overloads were resorted to; they demonstrated conclusively that the higher the finish, the better the endurance. The high finish must not be of the Brummagem or Reuleaux's 'cheap but nasty' variety.

"c. The **elastic limit** should be as high as can be had. A limit of proportionality above the elastic limit is desirable.

"d. The **hardness and uniformity of hardness** throughout the mass of the ball to the highest attainable degree is essential.

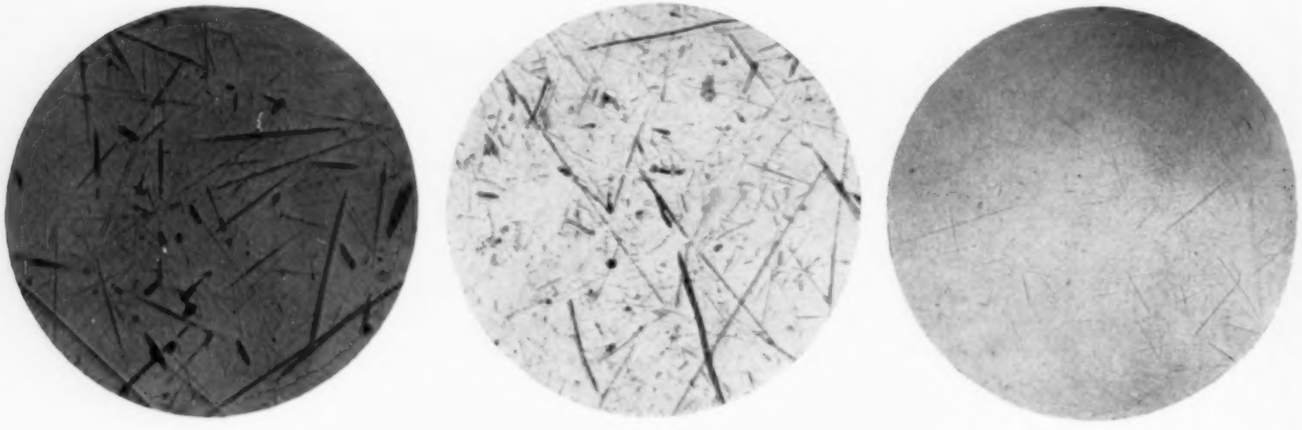
"e. **Correct knowledge** and uniformity are more important than even these requirements of high elastic limit and hardness. It will not do to say that, though some balls of a lot may do better than others, the balls carrying more than their share of the load, much as and with the same bad effects described while considering the truth of shape and size. Lower quality, provided it is uniform, can be allowed for. It will then merely affect dimensions."

Mr. Hess then went on to state that ball making machinery had arrived at a considerable state of perfection; but balls within a limit of 0.0001 in. of size are not being made without the sacrifice of other qualities, but it was perfectly feasible to select and grade balls within the desired limit.

He continued: "The hardware dealer's word on uniformity of size is not a safe guide; he is perfectly honest in throwing odd lots of ⅝-in. balls into one box and in thinking the customer who objects because they vary a half-thousandth or even two, a 'finicky crank'."

Thus in 1907 the ball and ball bearing manufacturers were talking of grading balls in lots which did not vary more than 0.0001 in. This was considered a *very* close tolerance for other machined parts, but was a *necessary* tolerance for good ball bearings. As equipment for the manufacture of balls has improved, so has the accuracy of balls improved. This is readily shown by the table on page 151 from the catalogs of the Hoover Steel Ball Co. published during the years indicated. Columns headed "Sphericity" represent the maximum variation in shape (random diameter) of any single ball of the grade indicated, and the figures in the columns headed "Size" represent the maximum permissible variation amongst the balls in any given package.

This table shows that the sphericity of Grade 1 balls is now less than 25 millionths of an inch deviation from true spheres, which in plain English means that the balls are almost as round as present day equipment can measure



1915 — A polished surface crossed by deep, long scratches

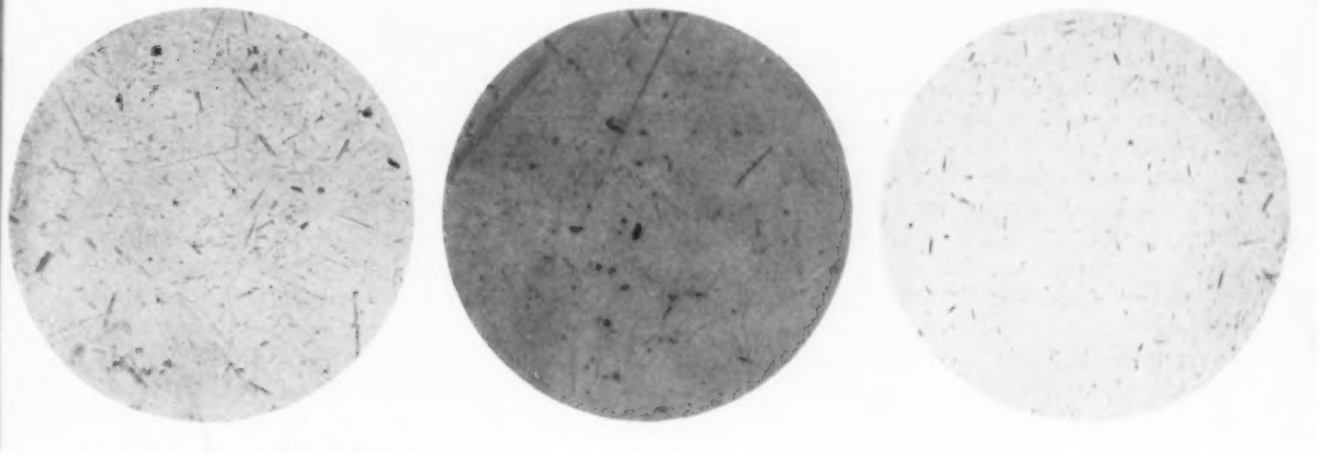
1918 — Scratches become shallower and shorter, but polish not quite so high

1922 — Very shallow scratches but fairly long; a high polish

Improvement of Ball Surfaces, 1910 to 1925. Magnified 100 diameters

them. The variation within one package of plus or minus 25 millionths also means that they are very close to one size and therefore a well-made race should distribute the load evenly among all of the balls in a bearing.

In the early days of ball making, hand methods left numerous variations in size, roundness, surface quality and steel quality which are gradually being overcome by machinery, proper auxiliary equipment, and technical control. The ball surface has always varied according to the method of manufacture and is more than a mere polish; it depends upon the method and care used in finishing. Accompanying photographs show differences in ball surfaces as seen



1928 — Scratches short and shallow but surface contains a few small pits

1932 — A few long shallow scratches and a bright finish

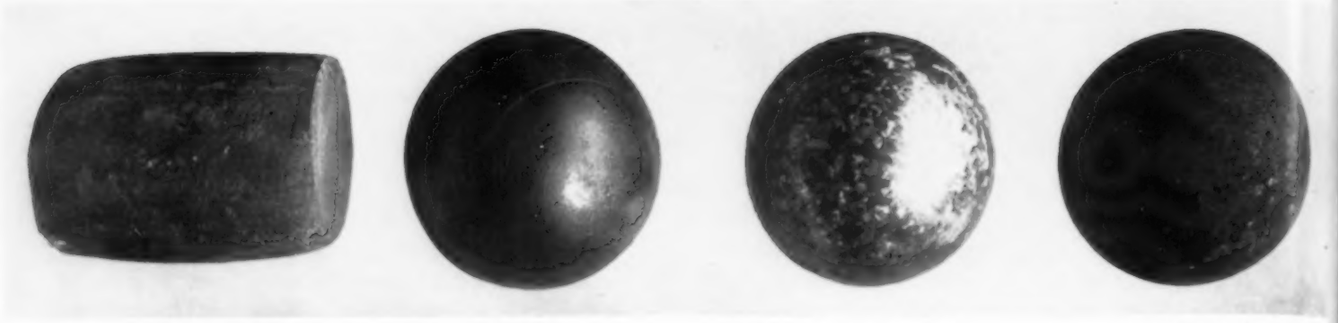
1937 — Short and shallow scratches, a very few small pits, high polish

Improvement of Ball Surfaces, 1925 to 1939. Magnified 100 diameters

under the microscope at 100 magnifications. These pictures could be dated 1915, 1918, 1922, 1928, 1932 and 1937. The first would represent the surface of a ball ground on a Hoffman grinder and polished; the next represents the same equipment but with improvements in size of grit and bond of stones; the next three represent further improvements in grinding and polishing methods; the last represents the highest quality of surface thus far obtained by the greatest care in handling and polishing. Any reader who has prepared photomicrographic specimens will appreciate the care needed in avoiding scratches of length and depth; these considerations are also essential for good ball and bearing surfaces.

In contrast is shown on page 151 Henry Hess's photographs of 1907 of the surfaces of three different makes of balls of that time. The magnification is only 35 times so that the two groups cannot be directly compared. These old balls were probably formed, rough dry ground, hardened, finished dry ground almost to size, and then polished in tumbling barrels. Richardson's dry grinder (and subsequent ones) consists of a flat grinding wheel and a flat steel plate rotating in opposite directions; the balls are between them. The balance of the machine acts as a guide to hold the balls in position and keep them from being thrown out by centrifugal force. Thus the surface finish was largely dependent upon the size of grit and pressure between the plates. This type of machine is being used in our present production (third step of "rough dry ground" in the view on page 154).

About 1910 Ernest G. Hoffman designed and patented a grinding machine whereby balls were ground in concentric grooves between an abrasive grinding wheel and cast iron plates, using kerosene or similar liquid for carrying away the grit. The Atlas Ball Co. of Philadelphia acquired the U.S. patents covering these grinders and later sold a one-half interest in them to the Hoover Steel Ball Co., thereby permitting the use of these machines. . . . This permitted the use of finer grit in the grinding wheels and therefore shallower cuts on the balls previous to polishing. This type of machine is used after hardening (see the view just mentioned); it also did the finish grinding of the balls shown in the series representing



Slug, Hot Sheared *Drop Forging* *Dry Ground Rough* *Heat Treated*

Various Stages in the Production of 3-in. Steel

surfaces of balls made from 1910 to date. The Hoffman grinder would be called a wet grinding operation; therefore it gives no opportunity for overheating the hardened steel balls with subsequent grinding checks.

Notes on Manufacture

Various steps in the production of Grade 1 balls are shown above. A slug is hot sheared (to avoid tears) from a rod, and this slug is drop forged into a ball and the flash trimmed. (Small balls, on the order of ½-in. diameter, are made in a cold header which cuts the slugs from wire fed into the machine and automatically forms them into rough balls.)

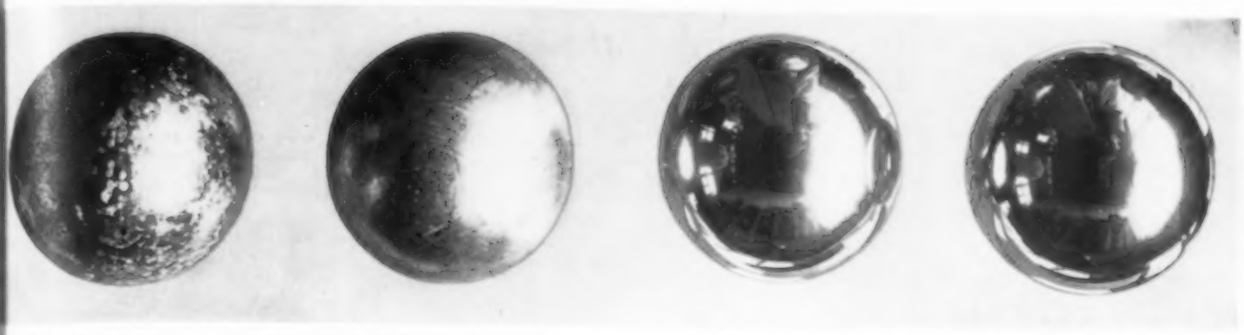
Dry grinders remove the flash and defects inherited from the surface of the wire and make the balls round. Heat treatment hardens and tempers the balls uniformly from surface to center. A series of Hoffman grinders decrease the size of the cuts and scratches, make the balls practically round and grind them almost to finished size. Tumbling in lime removes the "fuzz" from the previous grinding, while final leather polishing gives the balls the high luster so essential for ease of inspection.

All balls must be inspected carefully to make sure that they conform to our standards before they are oiled and packed for shipment. Inspection removes any balls containing steel defects, heading defects, grinding cuts, deep scratches, soft spots, or other defects visible either to the naked eye or under a hand glass. Grade 1 balls are reinspected to make sure that no cull might slip by. An interesting item in the final inspection room is a box used for "floor balls"; any ball regardless of size which is dropped on the floor is scratched and unfit for use in a high quality bearing. All girls working in this department are required to wear gloves to prevent the formation of "hand rust" on any of the balls.

Thus far the discussion has pertained to steel balls made of highest quality, electric furnace steel containing about 1% of both carbon and chromium. Plain chromium steel has been the alloy used in balls and bearings since the beginning. We vary the chromium content from 0.50% for small balls to 1.50% on large balls, in order to control hardenability so that all balls will be uniformly hardened from surface to center without a hard shell and soft core. Incoming steel is rigidly inspected to make sure that no seams, decarburization or slivers are on its surface and no pipes, porosity, hairlines, inclusions, overheated structure, or other defects are present internally. The heat treatment given the balls is carefully controlled so as to harden the balls uniformly, while each lot of balls is rigidly tested for hardness, crushing load, and nature of fracture before it is allowed to leave the department. All balls must be file hard and minimum Rockwell C-60. Hardness specification increases slightly according to ball size from C-60 for ⅛-in. balls to a maximum on large balls. An interesting jig is used in making the three-ball crushing test. Required loads vary from 1100 D^2 min. for ⅝ in. and smaller; 1000 D^2 min. for $\frac{11}{16}$ to 1¼ in. inclusive; and 850 D^2 min. for larger sizes. (D is ball diameter in eighths of an inch.)

Commercial "A Grade" carburized steel balls have been developed with close tolerances and good surface finish. They are adaptable for toys, small tools, and light machinery where speed is slow and the loads are light. These balls have a soft center and therefore deform under heavy loads to cause early flaking and failure, but do have a definite purpose to fulfill in proper applications.

Another interesting specialty is hollow balls



Dry Ground Finish *Oil Ground Rough* *Oil Ground Finish* *Burnished*

Steel Balls for Grade 1 Ball Bearings

for "Acme" ball bearing casters. Herrman A. Schatz describes their manufacture as follows: "Two hemispheres are punched from strip steel and butt-welded together. The flash of the edges is trimmed off and the hollow ball is re-struck between dies to make it round. It is then rough ground, carburized, hardened, and finish ground. The wall thickness varies according to ball diameter from 0.032 in. in ¾-in. balls to 0.065 in. in 1¼-in. balls."

Next in hardness to steel balls are stainless steel balls now used in some bearings and destined to more use as moving machinery is operated in corrosive conditions. The largest use of stainless steel balls is now in the oil industry for pump valves. Monel metal, bronze, brass, aluminum bronze, and aluminum balls are used for valves depending upon the corrosive media present and the weight desired.

Special uses of balls are so numerous that all cannot be mentioned. Such items as standard weights for certain laboratory tests is one. Another is an item of over one hundred million balls used annually for roller skates.

TIN COATINGS FROM VAPOR

By B. W. Gonser and E. E. Slowter

Abstracted from Technical Publication 76,
International Tin Research and Development Council

A TINNED SURFACE may be applied in many ways, such as dipping, wiping, electrodeposition, metal spraying. Another method which has been investigated only recently, but which shows interesting possibilities, is the deposition of tin from the vapor phase. This involves the decomposition of a volatilized tin compound at the surface of the metal object to be coated. Advantages to be gained by this method are chiefly ease in controlling the thickness and uniformity of the coating, particularly on articles of irregular surface, and the production of a hard tin alloy coating.

In vapor coating with tin, a volatilized tin salt is brought into contact with the metal to be coated under proper conditions of time, temperature, and atmosphere. The temperature is sufficiently high for the deposited tin to be molten and to alloy with the metal being coated. Thus, vapor coating may resemble cementation in its effect, with the advantage of having a moving atmosphere which can penetrate to all parts of the work. In referring to this method of coating metals with a tin alloy it has been convenient to use the term "stannizing".

In the experimental work, cylinder hydrogen, dried and purified of oxygen, was led over heated anhydrous $SnCl_2$ and immediately passed into a tube furnace containing degreased copper coupons. At those temperatures where the action proceeded, the amount of tin deposited was roughly proportional to the time. Very heavy deposits are therefore possible.

Since the vapor pressure of the reagent (stannous chloride) increases rapidly with temperature (10 mm. of mercury at 700° F. to 600 mm. at 1125° F.), the operation is better done at temperatures where the vapor pressure is high. For any action between the copper and the vapor to take place, a certain minimum temperature is required, found to be usually between 650 and 850° F. At temperatures above this threshold value

(Continued on page 184)

RECRYSTALLIZATION

Article for Handbook
By Robert F. Mehl
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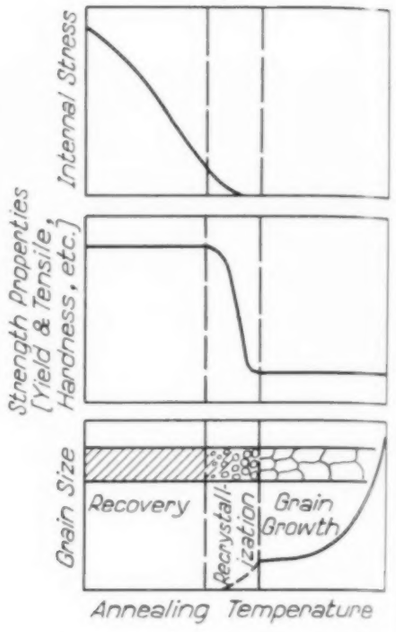


"Recovery" Is Relief of Internal Stress at Relatively Low Temperatures; Strength Properties Are Not Changed Much Until the Metal Recrystallizes at Intermediate Temperatures; Grain Size Increases Only After Heating at Higher Temperatures (Sachs)

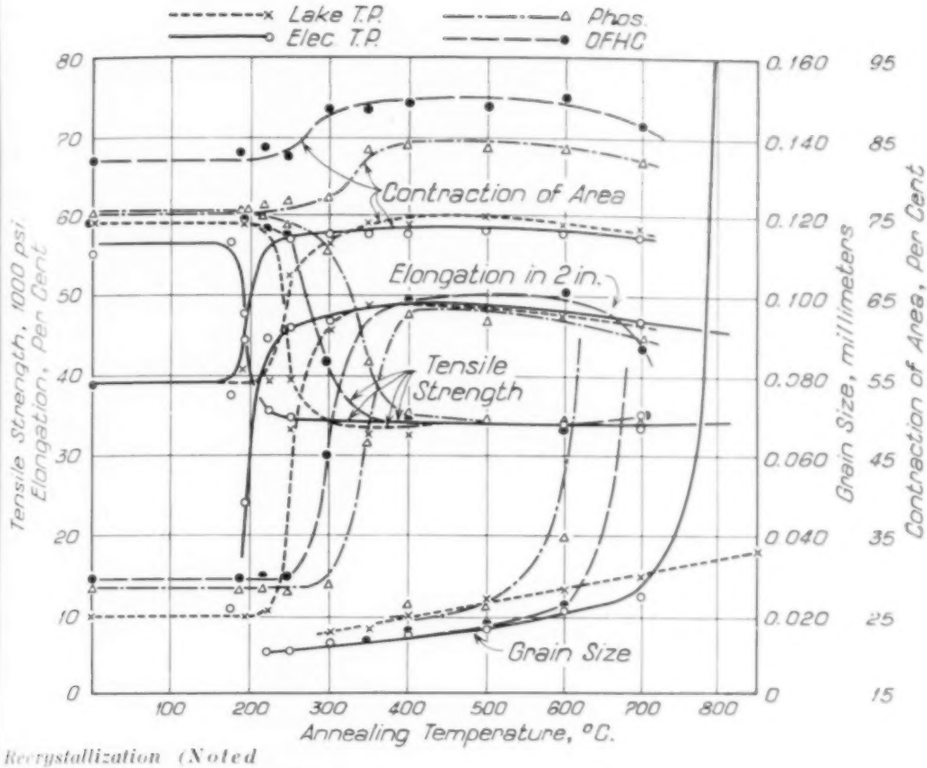
METALS which have been strained by cold working are not stable, but tend to revert to a strain-free state. This article will consider the processes, of which recrystallization is the chief, by which the effects of cold work may be relieved.

It may be said at the outset that cold work consists in plastic deformation at such temperatures and at such rates that no recrystallization occurs during the deformation process. Under such conditions the metal is strain-hardened. The compression of iron at room temperature, for example, is cold work; but the compression of iron at higher temperatures in the absence of recrystallization is also cold work. Only when such temperatures are reached that recrystallization (which leads to softening) occurs **during** the working process, can the term "hot work" be properly employed; in general, these temperatures are high in metals melting at high temperatures and low in metals melting at low temperatures — occasionally as low as room temperature or below.

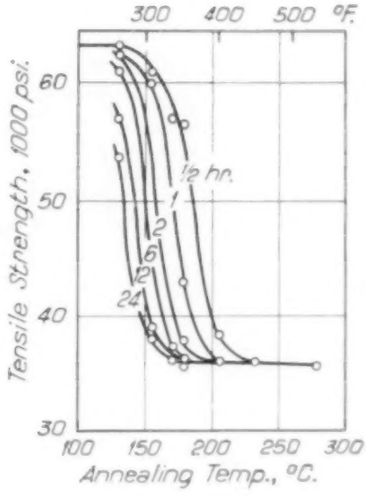
Such deformation produces fundamental structural changes in the metal. At low degrees of deformation, slip lines appear in those grains in which the slip planes are most favorably oriented for yielding; in metals which readily form mechanical twins, like zinc at ordinary temperatures, twin bands also appear; as the degree of deformation becomes greater, slip lines appear in an increasing number of grains, the grains tend to rotate, the crystal planes to become curved, and the grains to become sensibly elongated in the direction of flow. Since the directions in the crystal grain by which flow can take place are determined by lattice symmetry and are therefore not random, deformation is accompanied by the generation of preferred orientations, accompanied by corresponding directional properties. This deformation is accompanied by an increase in the strength properties such as hardness, yield strength, tensile strength, and a decrease in the ductility properties such as elongation, reduction of area at fracture, drawing capacity, impact strength. It is accompanied also by a slight decrease in density and electrical conductivity, and a decrease in maximum permeability, and by an increase in electrode potential and coercive force, and a slight increase in the coefficient of thermal expansion, and compressibility.

The atoms in an annealed metal are in a continuous state of thermal vibration about mean positions which are symmetrically disposed on a space lattice; apart from relatively minor imperfections, this is a geometrically perfect arrangement. The perfection of this arrangement, however, is grossly altered by deformation: The lattice planes become curved and twisted, atoms are forced into positions less symmetrically disposed, with resultant distortion of atom shapes and energy distribution, and increase in the internal energy of the metal.

The non-homogeneous character of cold deformation creates a pattern of internal strains. In commercial forming operations, the friction of rolls or of dies, or the complexities introduced by multiple types of deformation or by heat treatment, create internal "macroscopic stresses" ("Heyn stresses") in such a way that one section of a piece may be in tension while another is in compression. Furthermore, a pattern of stresses on a fine scale, "microscopic stresses", characterized by minute regions in which tensile (and compression) stresses occur, also is formed as a result of slip on atom planes, of the bend-



Recrystallization (Noted by Sharp Changes in Strength Properties) Depends on Presence or Absence of Minor Impurities, as Shown in Above Data by Pratt for Lake Copper (Tough Pitch), Electrolytic Copper (Tough Pitch), Phosphorized Copper, and Oxygen-Free High Conductivity Copper



Copper Wire, Cold Drawn 93%. Softens at Lower Temperatures if Longer Time Is Given at Heat (Alkins and Cartwright)

ing of slip planes, of slip on intersecting slip planes, and of the impedence to normal slip at grain boundaries. Such a pattern of stresses contains points of unusually high energy peaks, which are the points of least stability in the cold-worked metal where processes relieving the effects of cold deformation will originate. The greater the amount of cold deformation the greater will be the number of such peaks.

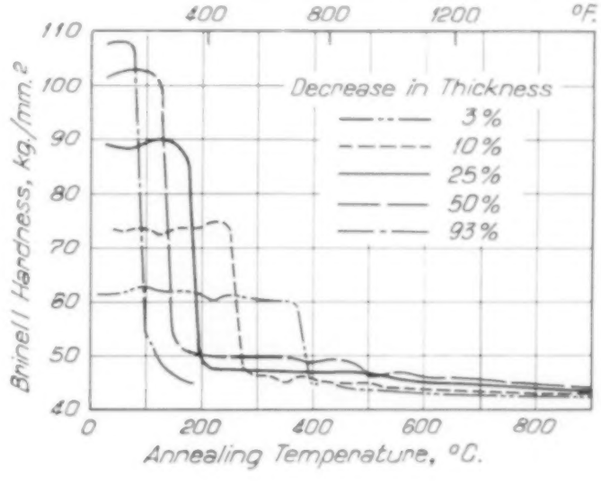
The heating of cold-worked metals results in a softening and accordingly a renewed ability to suffer cold work. This heating also relieves both microscopic and macroscopic internal stresses, either of which may be harmful in special cases—though generally cold-worked materials find widespread and wholly satisfactory applications. Macroscopic stresses can measurably decrease the fatigue strength of materials, can be conducive to failure in stress corrosion as in season cracking, and can lead to the yielding of structural members at loads below the normal yield strength.

The changes in properties which follow upon annealing are toward those obtaining before cold deformation, but the ways in which the various properties change on annealing are not simple.

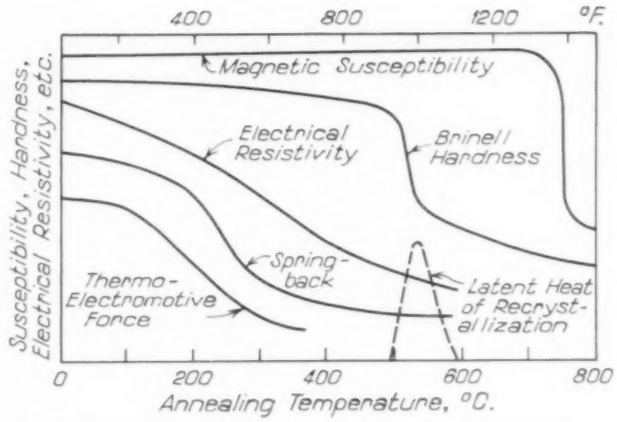
Three types of mutually distinguishable processes occur on annealing a cold-worked metal. These are: (1) Recovery, (2) recrystallization, and (3) grain growth, as illustrated in the first figure. **Recovery** is a change in the properties (particularly those determined by the state of internal strain) of a cold-worked metal at low annealing temperatures that is unaccompanied by any detectable change in the microstructure. **Recrystallization,** occurring at higher temperatures, is the formation and growth of new unstrained grains, supplanting entirely the cold-worked structure. **Grain growth,** occurring in completely recrystallized metals, is merely a continued growth of certain favored grains.

These three processes are all dependent upon time—they are

Softening Temperature of Cold-Rolled High Purity Copper Depends on the Amount of Work Done on It (Köster)



not instantaneous. The rate at which each operates increases rapidly with increasing temperature. When the temperature is sufficiently high, they appear to be instantaneous, but at lower temperatures the time dependence is readily detected. Actual rates vary widely from metal to metal and are greatly dependent on composition, purity, grain size of the sample before deformation, and the amount of deformation. Generally speaking, metals with low melting points exhibit high rates at low temperatures, as in the case of tin. Furthermore, the three processes sometimes overlap and are difficult to distinguish, while in other cases they can be clearly separated. The properties do not change concomitantly, as shown at right, and this often produces unusual combinations of properties.



Recovery in Iron Causes Large Changes in Thermo-Electromotive Force, Spring Back, and Resistivity. Iron strip, cold rolled 96%, was heated 60 min. at given temperatures and properties measured after cooling (Tammann)

Recovery, recrystallization, and grain growth all lead to softening. It is conventional to study these by heating cold-worked samples to a series of increasing temperatures for a certain time period, usually between 15 min. and 2 hr., and subsequently measuring the properties at room temperature. This eliminates time as a variable, and the results must be viewed with this limitation. In a narrow temperature range the change in properties is rapid, as shown in the curves on page 157 for copper of various degrees of purity, but this range may readily be displaced to lower temperatures by increasing the time of annealing (see the third figure). In a rough way, doubling the annealing time lowers the softening temperature by 10° C. The temperature of rapid softening is also decreased by an increasing degree of cold work, as shown in the last set of curves on page 157.

These curves of softening do not distinguish the three processes described above with certainty. Of the three, recovery should be considered first.

Recovery — The elongation of single crystals is characterized by a steadily rising stress-strain curve. If the load is removed and immediately reapplied, the stress continues from the point of interruption; if, however, time elapses, or if the piece is slightly heated, the stress begins at a low value, that is, strain hardening has been lost, though no recrystallization has taken place. This is "recovery", sometimes termed "crystal recovery". The process is most striking in single crystals but occurs also in aggregates.

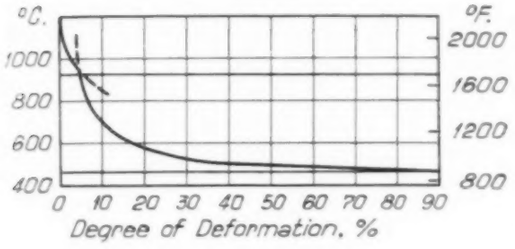
The effect of recovery in iron is shown in the sketch above, adapted from Tammann. Brinell hardness decreases rapidly upon recrystallization; only a very slight decrease as a result of recovery occurs before this. However, thermo-electromotive force and electrical resistivity decrease at much lower temperatures, and the change in these is complete before there is any detectable recrystallization. This behavior shows that the several properties do not change in a parallel way.

Recovery is especially marked in the relief of internal stresses, as shown by the curve for "spring back". The tendency to season-crack in brass, the magnitude of macroscopic stresses, and the general tendency to crack during fabrication are greatly decreased by annealing to induce recovery without recrystallization; such stresses in cold-worked steel can be largely eliminated by annealing at 850° F., at which temperature steel does not recrystallize. Complete stress relief can be more completely attained by annealing to higher temperatures, and this is the usual commercial practice. The process of recovery in metals is doubtless widespread, though experimental studies have not been sufficiently extensive to say when recovery may be separated from recrystallization and when these two processes overlap. In the latter case, distinction cannot be made.

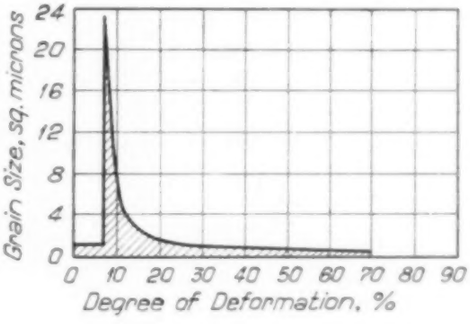
The causes for recovery are not clear. Recovery is doubtless a change in the internal stresses in worked metals, affecting primarily the elastic and electrical properties, but having relatively little effect on the strength and ductility properties. This stress removal may be associated with the straightening of bent slip planes, and perhaps with the healing of microscopic cracks; it cannot, however, be pictured as a complete relief of stress, for a metal which has recovered does not lose its capacity to recrystallize. The reasons for strain hardening are not well understood, and until the cold-worked condition itself can be more adequately described, it is unlikely that recovery can be more clearly understood.

Recrystallization — On heating a cold-worked metal to a sufficiently high temperature, or for a sufficiently long time at a somewhat lower temperature, new grains appear and grow, until ultimately a new grain structure has completely replaced the old. This is recrystallization. The accompanying changes in properties are in the direction of the restoration of the properties char-

acteristic of the metal before cold deformation (though these may not be exactly reproduced, for the final grain size may be different from the initial). The softening temperatures illustrated in the various types of copper (page 157), as shown by the rapid increase in elongation and decrease in strength, are generally the temperatures at which recrystallization occurs, but when the material has partially recovered before recrystallizing, the changes in strength properties do not sharply define the beginning of recrystallization, and when grain growth after recrystallization is pronounced the strength properties continue to change after the completion of recrystallization and thus do not sharply define the end; microscopic and X-ray studies are then required to define the beginning and the ending of recrystallization.



Within Limits, the Temperature Where Recrystallization Begins Varies Inversely With Amount of Deformation. General form of curve, at left, after Hanemann, is applicable to all metals; this one specifically refers to low carbon steel deformed at the temperature of recrystallization



"Critical" Amounts of Deformation Are Required Before Recrystallization Is Possible. Curve represents conditions for low carbon steel reheated to 950° C. (Hanemann)

Complete removal of the effects of cold work and the possibilities of controlling grain size, and thus particularly the behavior of the material toward further working, make recrystallization a process of immense practical importance. Unusually large grains are often highly undesirable, for they cause the familiar "orange peel" effect on drawn objects, and the tears in large worked sections. It is therefore of the greatest importance to know what factors govern it.

Recrystallization is the continuous formation of nuclei of new crystals and the growth of these nuclei until the system is wholly constituted of the new grain structure. The rate of formation of nuclei and the rate of growth of these nuclei are thus the basic factors, and it is necessary to inquire how these may vary with temperature, with time, with initial grain size, with degree of deformation, and with composition and purity.

Thus, recrystallization is not an instantaneous process but one which clearly depends on time. It is in this sense entirely similar to the formation of pearlite from austenite, giving rate curves of a completely analogous form. Most of the data, however, have been obtained by employing short and fixed annealing times, and thus give no clue to this time dependence.

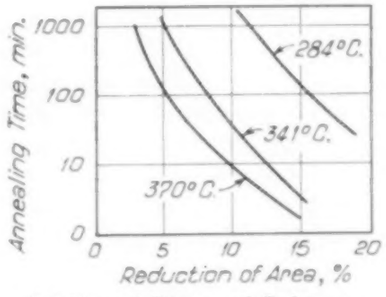
The new nuclei prefer to form at grain boundaries, slip lines, deformation markings of various sorts, and twinning planes. Recrystallization can thus most conveniently be detected metallographically, but the sharpening of X-ray diffraction spots and the appearance of new sharp spots can be used as a trustworthy criterion.

Apart from composition and purity four factors determine the grain size after recrystallization: (1) The amount of cold deformation; (2) the temperature to which the cold-worked metal is heated; (3) the time at this temperature; (4) the original grain size. The rate of heating to the recrystallization temperature is a further variable.

Several fundamental laws are now well recognized: (1) Recrystallization occurs at a higher temperature the smaller the degree of strain hardening. (2) Increasing time of annealing displaces recrystallization to a lower temperature. (3) The final grain size is chiefly dependent upon the degree of deformation and to a less degree on the annealing temperature; the final grain size is the larger the smaller the degree of deformation. (4) The larger the original grain size the greater the amount of cold deformation to give equivalent recrystallization temperatures and times. (5) The amounts of cold work to give equivalent strain hardening vary with the temperature at which deformation is done.

The first law may be illustrated by the top diagram on this page in which the beginning of recrystallization is plotted against annealing temper-

(Continued on page 192)



Relation of Degree of Deformation, Time and Temperature on Stretched Copper Wire (Sachs)

APPLICATION OF STEEL

to operations at

high temperature

By T. McLean Jasper
Technical Consultant
A. O. Smith Corp.
Milwaukee, Wis

IN DESIGNING structures to operate at elevated temperatures there are various factors which should be considered, depending upon the different requirements of the design.

For certain structures the designer may need to consider only the fundamental strength of the material, while for others he will also need to consider the stiffness of the structure in order to accommodate small clearances between moving parts under load. The stiffness factors in flexure or bending are the modulus of elasticity (a function of the material) and the section moment of inertia (a function of the cross section—design) usually designated as E and I, respectively, and in torsion they are the modulus of rigidity or shear and the section polar moment of inertia usually designated as F and J respectively.

Designs, therefore, may depend on a factor of safety based on strength of the material, or they may be controlled entirely by considerations of stiffness, or perhaps a combination of both strength and stiffness may be essential. Needless to say, the values must be applied to the most adverse working conditions that the structure is to operate under.

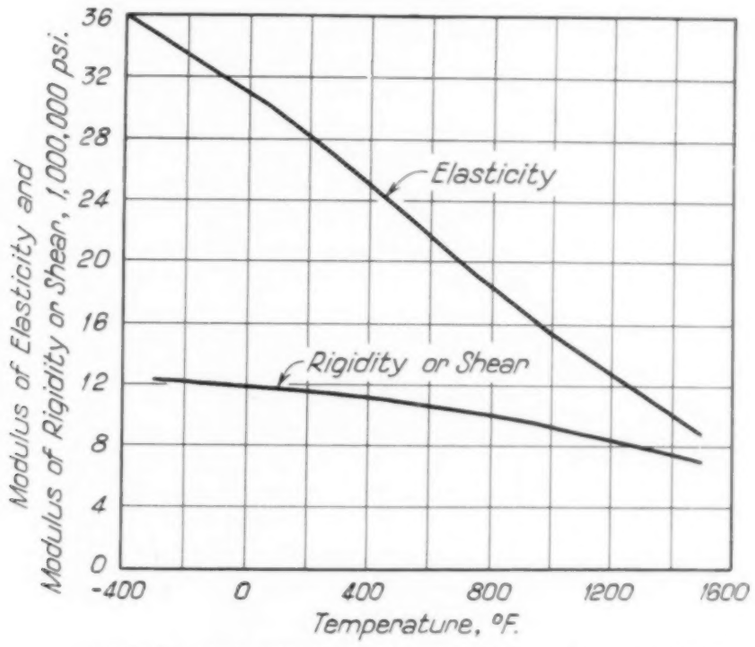
The engineer who designs a steam turbine with rotors made of disks, which depend on stiffness to reduce deflections and vibrations, needs to consider primarily the stiffness under operating temperatures that control the maximum deflections he can accommodate, and secondly the stresses which are involved in these deflections. Such stresses may be nominal or they may reach values which call for good judgment or knowledge as to the physical properties of the material. The designer of a pressure vessel to operate at high temperature, on the other hand, needs to consider the "long-time ultimate strength" and "long-time yield strength" of his

SOME equipment, such as turbines in super-power plants, must not only retain strength at high temperatures, but their dimensions must not change beyond small limits. For such equipment time consuming creep tests are necessary. For many pressure vessels a much larger change in size is of no importance, and shorter testing procedure is adequate. The author describes such test and design methods used successfully for much chemical and petroleum equipment.

material for the working conditions (including occasional over pressures) and the effects of corrosion.

For such important work it is believed by the writer that the most vital consideration is some method of arriving at reliable strength and elastic properties of the material on which to base designs — data that will not overestimate the properties of the materials to be used nor create a feeling of uncertainty in the designing engineer's mind.

For service at ordinary temperatures the physical values used are the ultimate and yield strengths, and at times the fatigue strength. (The need for ductility and the demand for it in specifications is usually associated with fabrication needs and small operating adjustments.) For carbon and low alloy steels, the values at ordinary temperatures of E and F are 30,000,000 and 12,000,000 psi. respectively, or so near these values that it makes very little difference.



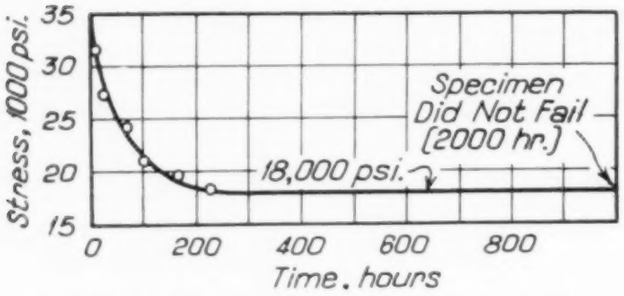
Modulus of Elasticity in Tension of Carbon and Low Alloy Steels Decreases Sharply With Temperature, Whereas the Modulus in Torsion (Shear) is Relatively Constant. After Sutherland

Uncertainty in Test Figures

However, as operating temperatures are increased, the values of E and F are decreased progressively. For a fixed elevated temperature, the values of E and F for carbon and low alloy steels are as constant as they are at ordinary temperatures. Frequently, however, values are published for a given elevated temperature which show a wide variation. The writer believes that this is associated with the difficulty of obtaining a known and uniform temperature over the full gage length of the specimen and the difficulty of obtaining extensometers which retain their accuracy and sensitivity when introduced in the heating medium. The curves for E and F presented herewith are based upon the "Kinetic Theory of Solids" by Sutherland (see *Philosophical Magazine*, October 1923, under "Use of Energy Relation ....." by Jasper), and are plotted from tests made on relatively small diameter specimens, thus tending to insure uniform temperature over the entire gage length.

As was remarked above, there are a considerable number of values presented in the literature which are obtained from relatively thick specimens in which the question of uniformity of temperature can be questioned very seriously, and these are apt to show higher and in some cases much higher values than the results indicated by the two curves in the first figure. The latter may then be used for conservative values to determine the rigidity or stiffness of steel structures at various temperatures.

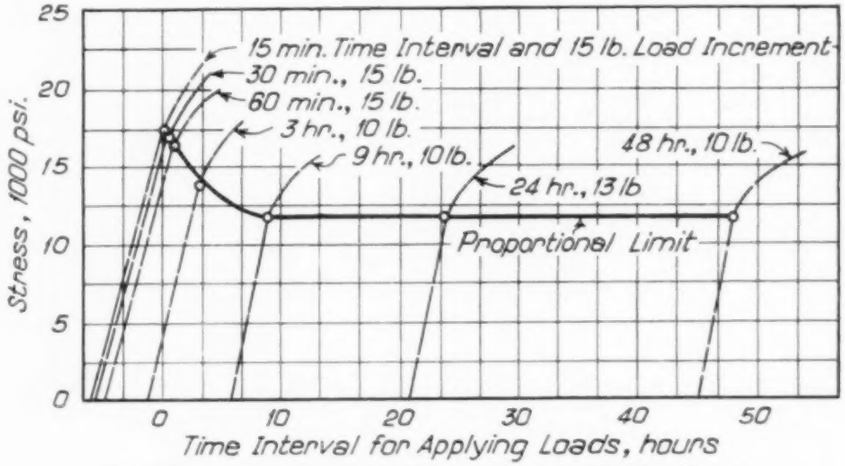
To answer the question as to the ultimate strength and yield strength of steel at elevated temperatures (the properties the designing engineer has long been in the habit of using at ordinary temperatures) requires an approach from a different direction from that associated with creep testing. This, it will be recalled, requires that a tension specimen under steady load be maintained indefinitely at rigidly constant temperature, and the extension — if any — be accurately measured and plotted against time. If one might inject a friendly criticism as to this method of testing it is to the effect that it does not lend itself to consistent results which correlate with a fixed value for a given class of material. "It is known that successive heats of steel of almost identical analysis and history will differ greatly in creep characteristics," in the words of Messrs. White, Clark and Hildorf before the 1938 Western Metal Congress (METAL



Long-Time Tensile Strength Determined by Loading Several Heated Specimens and Noting Time for Fracture. Above is the result for 0.25% carbon steel at 900° F.

of stress obtained from that portion of the curve which is parallel to the time axis represents the stress that the steel can carry for an indefinitely long period of time.*

This method of test was first outlined by H. J. French when on the staff of the National Bureau of Standards. (See a discussion in A.S.T.M. *Proceedings* for 1925, II, page 12). The data plotted at left indicate that at 900° F. the short-time ultimate strength of 0.25% carbon steel is about 35,000 psi., while the long-time ultimate strength is 18,000 psi. In designing pressure vessels for operation at 900° F. a lower factor of safety, based on the long-time ultimate strength, is used than though the equipment was to operate at ordinary temperatures, for the reason that short over-loads



Long-Time Proportional Limit Determined by Plotting Stress-Strain Curves of Heated Specimens Loaded at Slower and Slower Rates. Above is result for 0.25% carbon steel at 900° F.

PROGRESS, March 1938, p. 266). In trying to apply such results the engineer becomes bewildered with the numerous considerations with which creep testing is involved, and as a result he is brought to a state of uncertainty even in designing structures which heretofore he has built with certainty and which have a long, successful performance record behind them.

The author has long used the methods described below for obtaining ultimate and yield strengths and applied them in designing equipment for working at temperatures up to 1000° F. in continuous operation. A careful study of testing methods was first made. It was well known that at elevated temperatures steel may have an ultimate strength which is considerably below that value determined at ordinary temperatures, and that its long-time strength at an elevated temperature is considerably below its short-time strength at the same temperature. This relation between long-time strength and short-time strength is clearly illustrated in the above curve of test data for a 0.20 to 0.30% plain carbon steel at 900° F. The method of testing is to take several specimens of a particular steel and, at a definite temperature, to load each to a different constant stress until failure occurs — or until the load is maintained without failure for a very long time. The time for failure and the test stress for each specimen is then plotted and the resulting curve drawn, which applies of course for a single test temperature. The value

*Editors' Note: White, Clark and Hildorf in the 1938 Western Congress paper already quoted use the same method in their "stress-rupture test", and find that their results plot as a straight line on log-log paper, thus indicating that the longer the time at temperature the lower the rupture strength. A proponent of creep testing would also quote the A.S.T.M.-A.S.M.E. joint committee's publications showing that a 0.35% carbon steel would creep continuously (flow or extend in line with the stress) at a rate of 1% in 10,000 hr. at 850° F. if loaded at 7500 psi. Small creep rates are also observable by precise equipment at loadings considerably below the "long-time limit of proportionality", to be described in the closing paragraphs. These dilemmas would doubtless be avoided by an engineer using Mr. Jasper's methods when he selects a proper "factor of safety".

are resisted by a much higher factor of safety at high temperatures than though the steel were in service at ordinary ones.

So much for the ultimate tensile strength. How about the yield stress at elevated temperatures? The last figure shows the test data which were obtained in a different manner and represent the long-time and short-time limit of proportionality for this steel at 900° F. (This method of testing was first applied by the author in 1928.) Each stress-strain curve represents a different rate of loading. The value of the limit of proportionality for each rate of loading is plotted along the stress axis, and the time during which each load was allowed to exert itself is plotted along the time axis.

It will be noted that the proportional limit is higher for the more rapid rates of loading and approaches a constant value as the time increases between increments of load. The constant value which the curve approaches has been called the "long-time limit of proportionality". It is believed that the long-time limit of proportionality at 900° F. can be obtained on a single specimen of carbon steel if the interval between load increments is greater than nine hours. For different steels this time-increment may be somewhat different but the principle is indicated in the figure. It is seen that the long-time value is 11,700 psi., and the short-time value is 18,000 psi. for 0.20 to 0.30% carbon steel.

Methods Used for Design

For the engineer who is designing to close limits of deflection under elevated temperature conditions, the above method, which is believed to represent the very long time yield of the steel at elevated temperature, is of primary importance. It corresponds to the yield values used in designing steel structures at ordinary temperature. This, with a proper application of the stiffness factors, is believed to represent the engineer's method for safely designing equipment for elevated temperatures. Since 1926 the above general method has been used by the author and has entered into the design of a large number of pressure vessels to operate up to temperatures of 1000° F. continuously.

Equipment of Unusual Size, Taxing the Ingenuity and Facilities of Fabricators, Railroads and Erectors, Is Demanded by the Petroleum Refineries. Photograph courtesy Lincoln Electric Co.

CRITICAL POINTS

a week's diary

TO THE IRVIN PLANT near Pittsburgh which Carnegie-Illinois has just finished. It exhausts the superlatives of any except those who have already seen several of these tremendous sheet mills, and even these must express their admiration of some aspect of it or the manifold auxiliaries and finishing departments, capable of doing by the ton what the outmoded hand mills did by the pound. Not least amazing is Howard McIlvried's unseen organization which constructed this 60 million dollar machine in 18 months. Granted that the equipment is more or less standardized, that the work was done by a thousand contractors, and that months of preliminary planning preceded the ground breaking ceremonies — still an admirable staff must have cooperated admirably from first to last.

Continuous Sheet Mill

One rather intriguing point concerns the cold rolling mills. When such a continuous mill slows down the emerging strip goes off gage — becomes thicker. No very obvious reason exists; the roll housing and rolls themselves should be under practically the same forces and their elastic action not measurably different. Men in the plant pointed out that the action is a combination of squeeze between the rolls and tension on the emerging strip from the power-driven coiler — the action is related to wire drawing, only in this case the die is the slot between upper and lower roll. When the speed of the mill is reduced, there is a lag in tension control, momentarily reducing the pull, whereupon the reduction from stretch is less than when the machinery is running under more accurate adjustment at top speed. (If this is true, a new robot will soon be devised to watch over this detail!) Professor Trinks of Carnegie Tech believes it rather has to do with lubrication: The strip is flooded with oil and at slower speed more of the oil is squeezed out between rolls and strip. This increases the friction and the pressure required. The greater the pressure, the longer the arc of contact, the more the friction, the greater the pressure, and so on in a decreasing series until a new balance is set with a slightly stretched housing and a slightly off-gage strip.

At Rochester heard Thomas Wright, technical director of Lucius Pitkin, Inc., give a talk wherein a research man appeared as a transmuted Sherlock Holmes, surrounded with all the apparatus of an Irving Langmuir. Plenty of scientific material for mystery stories already exists; thus, Frederic Emery of Harshaw Chemical Co. was recently star witness in a case which put a couple of Cleveland safeblowers into safe keeping; he showed identical spectrograms of particles of cement found in their trouser cuffs and from the blown vault. Another recent example from Wright's laboratory had to do with whether a bullet had been fired through a screen door — spectrograms of the wire at the edge of the suspected puncture showed lines belonging to lead and antimony; elsewhere the screen wire was free of these elements.

Ferreting With the Spectrograph

William Campbell, late professor of metallurgy in Columbia University, was never so happy as when he was doing some high class detective work on ancient coins. Sherlock Holmes's magnifying glass in his hands became the metallographical microscope. Some of the evidence it uncovered has not yet been adequately explained. For instance, in a series of coins from Asia Minor the oldest were bronzes containing 10% tin, and the youngest were tin-free brasses with 15% zinc. Is this an example of debasing the coinage, or (more likely, since it was a gradual change over several reigns) an early example of metal progress? In another group of ancient metal objects is one made of tin as pure as any of today's commercial brands. How did it get there, and who then knew that much about smelting and refining?

Relationships between minerals and metals — and, contrariwise, distinctions as to place of origin — discovered by spectrographic analysis

have always fascinated Tom Wright. One such examination was of a group of exquisitely molded iron articles, all alike and presumably castings. The archeologist doubted whether the foundry art of that ancient period was far enough advanced to produce such forms, and a quick metallurgical examination proved them to be wrought iron (not cast) and therefore hand worked. This, though, is strange: Another similar group was of alloy iron with nickel and cobalt. Where did that metal come from? Not from a chance meteorite for the proportions are not right.

All these matters are reminiscent of a conversation years ago with Stephen Grancsay, curator of armor at Metropolitan Museum of Art. Grancsay was of the opinion that the innumerable counterfeits could be indubitably recognized by errors in design, ornamentation, methods of fabrication and a lot of intangibles. It was suggested that the spectroscope might clinch the proof; Toledo sword makers of a given period probably used metal from a very few favored sources — maybe all in a single mining district. Spectrograms would show family relationships in the slag contained so generously in old iron and steel. To match this the counterfeiter would have to spoil a veritable antique to get his raw material!

To Glenn L. Martin's fine plant near Baltimore for building transport flying boats and fighting aircraft, where Reid Gray, chief of laboratories, and Marsh Powers, assistant to president, explained the operations — in all except one huge new building where Uncle Sam is doubtless preparing some surprises in the gentle art of bombing. Thanks to a considerable concentration of work on one very successful design, the Martin plant most nearly approaches systematic, straight-line production, but even so more than 3000 men each day are required to cut and form and weld and rivet and design and test the multitude of parts which when assembled make one airplane. Sectional construction is highly developed. Nose section, center section, tail section, engine section, wing section are each completely built and all inside fittings installed before reaching the main assembly. Here the units are "plugged in" (as an engine is attached to its mounting), wiring and control cables drawn through, and the ship is ready for test flight. Possible disadvantages of such a scheme resulting in a heavier structure are evidently more than counterbalanced by such practical advantages as small assembly floor, quick disassembly for shipment overseas (where many are now going, it is hoped never to return unwelcome), quick reassembly, quick replacement of damaged units. Notable details of construction involve the use of slightly countersunk flat-head rivets flush with the outer skin, and the growing use of spot welded aluminum parts as test data accumulate showing their resistance to stress. The ship's structure is almost entirely of strong aluminum alloys. Plastic products, much discussed in British aeronautical journals, are used in transparent cockpit enclosures and various forms of sheet and tubing for non-structural parts; their use in basic structural members will await the outcome of extensive research now in progress. Gray also demonstrated a development of Martin's — gasoline "fuel cells" of rubbery stuff, almost non-leaking after shot through with a bullet.

Bombers — One a Day

In the afternoon to Rustless Iron & Steel Corp. where Alexander Feild, consulting metallurgical engineer of the firm (and a pioneering investigator of the subject, himself) explained that the interesting melting methods used there by Ronald Wild were abandoned in 1932 for a more efficient and flexible operation. Three Heroult arc furnaces are now available, each capable of turning out a 12-ton heat every six hours on bottom linings of chromite brick. Raw materials for melting are stainless steel scrap, chrome ore, and high carbon ferrochrome; these are charged with low phosphorus steel scrap in such amounts as required for the desired ingot analysis and in accordance with relative costs at the time. Roll scale is also charged originally so that the slag is essentially a mixture of iron oxide with an increasing amount of chromium oxide (the latter comes from the chrome ore and from the oxidation of chromium from the metal). The melt-down is very hot, and in about two hours the carbon is driven to 0.07% or lower, at which time about half of the entire chromium is in the pasty slag, half in the metal beneath. Thereupon lime and ferrosilicon are added as rapidly as they can be absorbed by the slag and in sufficient amounts to throw the iron and chromium back into the metal bath. When this is practically complete the first slag is skimmed and a

Chromium Recovered From Ore and Scrap

new lime slag is made up, under which the final adjustment to composition is done.

Metal is cast into 6-ton slabs for American Rolling Mill Co.'s sheet-strip mill at Butler, Pa., and into 10-in. square ingots for rolling into bars and wire rods in Rustless' own mill. Wire products seem to be the most in demand, other than sheet. At Baltimore the annealed and pickled rod is dipped in lead, and this soft metal acts as lubricant in the drawing dies. Lead must be removed by acid before process annealing, done "bright" in a long furnace. The wires go into nickel-chromium tubes and out through water-jacketed prolongations; the protective atmosphere is dissociated ammonia, dried over activated alumina. Stainless can apparently be heated in dry, really *dry*, hydrogen-nitrogen for some time without discoloration.

In Washington and to the Bureau of Standards to chat with old friends in the Division of Metallurgy. Most attractive of all the researches there on silver, heading up to Albert Dornblatt, is that concerning silver coatings for containers. The lowly "tin can" costs say 2 cents, but a billion are made every month; each can has 0.00008 in. of tin on it worth ⅛ cent. The aim is to replace this with 1 to 3 cents worth of silver. This extra price should be no obstacle for use with quality foods and beverages if the silver plate can prove expected advantages — either in use, such as no effect on delicate food flavors even when the can is opened and kept a few days in the refrigerator, or in fabrication, as less cracking at sharp bends at the seam (which has caused lacquer to replace some tin already). Non-porous electrolytic coatings 0.0002 in. thick have been obtained, with a good chance for thinner ones.

Too Much Silver

In view of the tremendous stakes involved, this American Silver Producers Research Project, now a couple of years old, got under way none too soon. Under the general direction of Lawrence Addicks, veteran expert in refinery problems, its avowed aim is to discover new industrial uses capable of absorbing 100 million ounces of the metal annually, and if attained would about treble the world's consumption in the arts and industries. World production of new silver is about 270 million ounces annually, and at least 200 million of this is useless. Once upon a time it would be bought for coinage or bullion, but today China, India and other minor countries find it undesirable to use it so — in fact, it is better for them to trade their coins and hoards to the American Government for commercial credits. This present price of silver is therefore fictitious, and will last only until the U.S. treasury becomes satisfied it has enough silver in its vaults or is told by Congress to keep hands off.

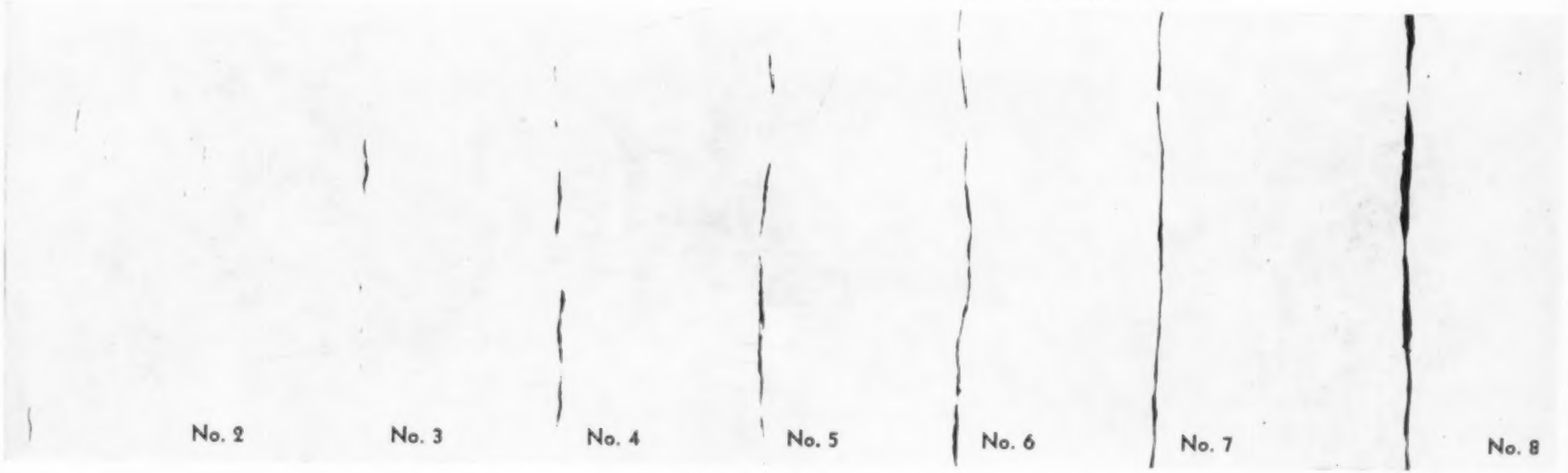
Reading in John Marsh's new book on Alloys of Iron and Nickel a quotation from Bragg and Williams on "relaxation time", that is, the time required for an unstable alloy to reach equilibrium by diffusion, to the effect that if equilibrium is substantially reached in one second at 500° C., the same sample would have required one hour at 350° C., several days at 270° C., and 30,000 years at 200° C. It might have been added, "geologic eons at 0° C." This picture of the enormous length of time required for atoms to fall into equilibrium positions at low temperature may have some relation to the non-success of attempts to form coarse Widmanstättan structures, typical of meteorites, in artificially compounded iron-nickel alloys. It appears that the iron-nickel solid solutions (meteorites) "freeze in" at about 500° C., for the iron and nickel atoms are so alike that their separation by different diffusion rates and the desired transformation of gamma solid solution into alpha is stopped cold — that is, in finite time in a laboratory. A meteorite has had infinite time; even though its temperature be close to absolute zero, many of the sluggard atoms like the tortoise have reached their goal. (Marsh notes another plausibility — that meteorites are cosmic trash from a shattered planetoid, which in its earlier history had stayed millions of years at just below the transformation temperature, where atomic mobility was enough to speed the diffusion.)

Time is Long and Art is Fleeting

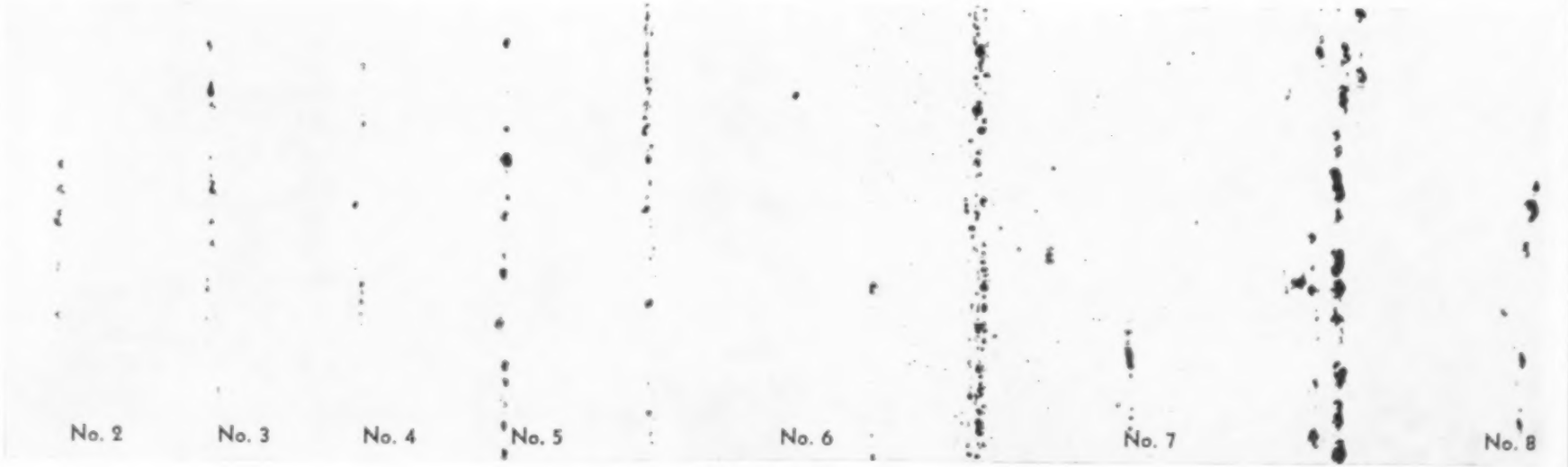
The matter of reaction rates is worth emphasizing; few are on guard against misleading reports of "stationary state" or "equilibrium", which are often merely a result of the life span and patience of the observer. Some confidence may, in fact, be put in results extrapolated from a consistent series of tests at higher temperatures. Arresting statements of this sort are quoted by Marsh: That pearlite will spheroidize in carbon steel at atmospheric temperatures in 10^{38} years, and that the vapor pressure of tungsten at 25° C. is 10^{-150} atmospheres, or about one atom to the known universe!

Rating of Inclusions ("Dirt Chart")

In use by Chevrolet Motor Co. *Developed by George W. Walker*



Silicate Slag Inclusions



Oxide Inclusions

THE SCOTCH HAVE A VERSE FOR IT

Tender-handed stroke a nettle
And it stings you for your pains.
Grasp it like a man of mettle
And it soft as silk remains.

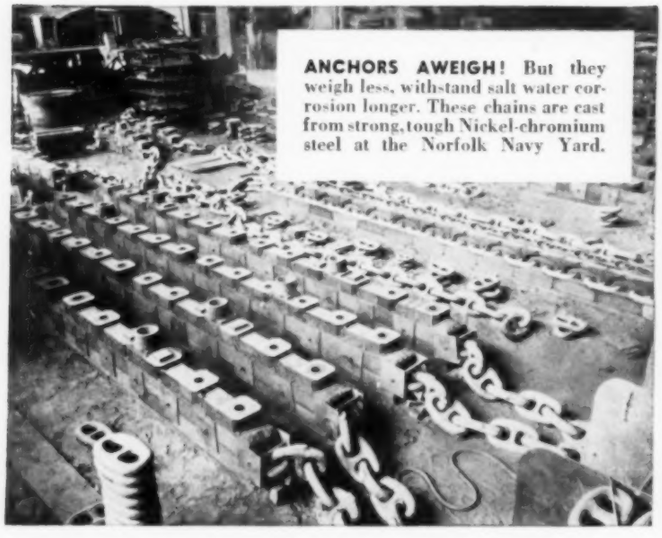
—old Scotch proverb

THIS YEAR, don't temporize. Don't try to get by with materials which were good enough in less competitive times. Use modern alloys containing Nickel to cut production and operating costs, reduce the heavy tax imposed by corrosion and wear.

Nickel helps each ounce and inch of metal do more work at lower cost per year. Nickel aids in solving many of the thorniest problems confronting you in 1939. The helpful suggestions of our research engineers, their practical experience in solving similar metallurgical problems for other businesses, are yours for the asking.

LANDSLIDES CLEARED QUICKER because this shovel is 28% lighter. Harnischfeger Corp., Milwaukee, makes it of a light-weight design using high-strength Nickel alloy steels.

NICKEL ALLOY STEELS



ANCHORS AWEIGH! But they weigh less, withstand salt water corrosion longer. These chains are cast from strong, tough Nickel-chromium steel at the Norfolk Navy Yard.

TWO POUNDER GRINDS AT 50,000 RPM! For the vitally important spindle of this fly-weight, air-driven grinder and die finisher the Onsrud Machine Works, Chicago, uses SAE 3135 steel toughened and strengthened with Nickel.

THE INTERNATIONAL NICKEL COMPANY, INC., 67 WALL ST., NEW YORK, N. Y.

CORRESPONDENCE

Rating of Inclusions ("Dirt Chart")

DETROIT, MICH.

To the Editor of METAL PROGRESS:

Several million pounds of steel has been rated for cleanliness in the metallurgical laboratory of Chevrolet Motor Co. during the past ten years, for which a useful rating chart has been devised. [See the data sheet, page 167.] It is to be used in connection with the deep etch test, as described below, using 4-in. bars of S.A.E. 4615-A steel for ring gears as an example.

The bars are marked with heat number at the steel mill, also as to whether from top, middle, or bottom of the ingot. Six samples are taken from a 50 to 75-ton heat, two from bars rolled from the top, two from the middle, and two from the bottom of the ingot. These samples are sheared from the bars, and are generally 8 to 9 in. long. Transverse sections are then sawed from the middle of each sample, about ¾ in. thick.

These transverse sections, properly marked for identification on their narrow edges, are next placed in a shaper and a light cut taken across one surface to remove saw marks. This surface is now ground against the side of a medium fine grinding wheel to remove most of the tool marks.

Deep etching is then done in earthenware pots about 10 in. diameter and 12 in. deep, half full of 1:1 hydrochloric acid (c.p.), and heated to 170 to 180° F. Samples are placed on edge around the wall of the pot so as to expose the ground surface to the free action of the acid. The time required is about 60 min.

Etched samples are washed with hot water, scrubbed with a plater's brush, and dried in an air blast. They should show a bright, clean surface with no finger marks, nor smeared and spotty areas. This operation should therefore be carefully done with clean pots, rubber gloves, and brushes.

We now proceed to their examination. The samples should be placed in order (top, middle, and bottom samples) under a good light. The general appearance is shown in the macrograph on the next page. Such sections prove the soundnes of the metal; we look for the presence or absence of primary or secondary pipe, carbon and ferrite segregation, non-metallic inclusions, internal ruptures. The mold pattern is generally a marked feature; examination of a large number of heats has shown a progressive decrease in size of mold pattern from bottom to top of ingot.

As we are now interested more particularly in non-metallic inclusions, the etched cross-section is carefully examined for them. This requires some experience and knowledge as to appearance and type.

We have found two general types of inclusions — oxides and fusible silicates. Oxides are generally rounded particles and occur as isolated dark particles or masses arranged in bands, or in continuous, somewhat ragged bands as shown in the micrographs (page 167). The fusible silicates are generally fairly long, mostly continuous, varying from thin sheets (appearing as threads on a polished surface) to fairly thick in cross-section, having fairly sharp outlines. Silicates are lighter in color than the oxide inclusions.

In the deep etched sections the silicate inclusions appear as sharply defined, nearly white, small areas only slightly attacked by acid. The inclusions indicated in the macrograph, on the other hand, are of the oxide type.

Once the inclusions are located, microsections are cut as indicated. Care is taken in sawing out these samples to cut slightly to one side of the inclusion so that after grinding and polishing the surface parallel to the longitudinal direction of rolling, the size and appearance of the inclusion will be shown to the best advantage. In this particular case, after cutting out and polishing the microsection, a No. 10 oxide inclusion was found (much worse than No. 8 of page 167) resulting in the rejection of this steel as too dirty for use.

Generally we have found objectionable

inclusions in the outer fourth of the cross-section of the bar. In sections cut through the mold pattern we have not found marked inclusions in this type of forging steel.

Polishing for micro-examination for non-metallic inclusions requires considerable care and experience. Excessive pressure should be avoided. The section should be rotated on the polishing wheel so as to obtain a uniformly polished surface and avoid disturbance or undue scoring of the inclusions and the metal adjacent thereto.

Ordinarily three sections are polished for examination, one each being taken from bars rolled from top, middle, and bottom of the ingot and representing the most marked inclusion found in each by deep etching. The polished sections are examined at 100 diameters, carefully and systematically, and the location, size, number, and appearance of all inclusions noted, compared with the chart and rated accordingly. It is frequently found desirable to regrind and repolish a specimen. Occasionally an inclusion is found the whole or the principal part of which extends to the edge of the polished surface where an inclusion was indicated by deep etching. In this case part of the inclusion and some of the surrounding metal have been removed by the action of the acid. Such inclusions are disregarded in rating the sections, only those lying wholly within the polished surface being considered.

The cleanliness of the steel is indicated by the corresponding numbers on the chart. It will be noticed that these numbers range from 2 to 8 inclusive. (The original chart contained 20 micrographs, ten of each type which were numbered from 1 to 10.) The rating is purely arbitrary and consequently any acceptance or rejection as to cleanliness based on it is equally so. However, we generally regard steel containing inclusions rating below No. 5 fusible silicates or slag, and No. 6 oxides as objectionable for use in gears. If such objectionable inclusions are found, all of the samples brought to the laboratory are examined and additional samples are obtained of such parts of a heat as may be considered useful, subject to more detailed examination.

GEORGE WARREN WALKER

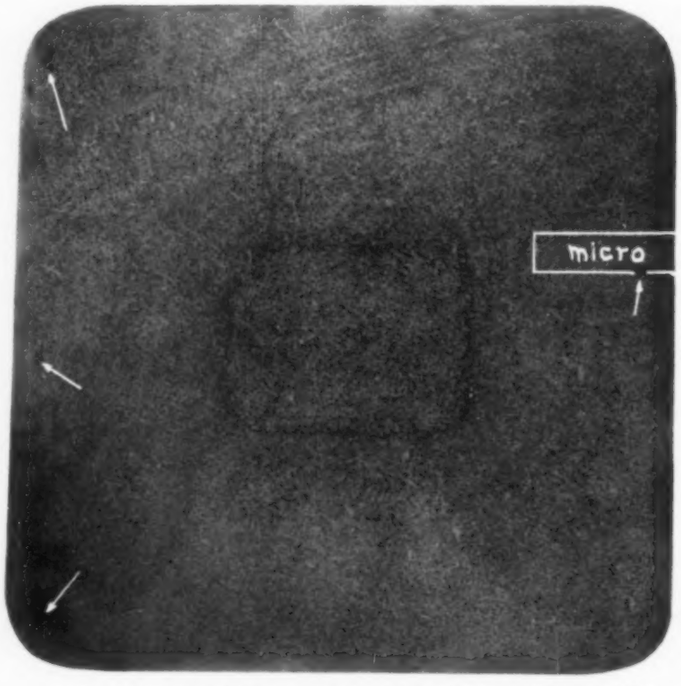
Stabilization of 18-8
unnecessary in many applications

SHEFFIELD, *England*

To the Editor of METAL PROGRESS:

The Henry Marion Howe Memorial Lecture which Dr. Frederick M. Becket gave last February to the American Institute of Mining and Metallurgical Engineers contained these sentences: "For many years intergranular corrosion was one of the serious problems facing the stainless-steel metallurgist. Today the problem is well understood so far as prevention and cure are concerned, and indeed it might well be relegated to the sphere of academic interest." While the last sentence may be true in some respects, there is not a little evidence that certain practical aspects of the problem are not always clearly understood. This applies particularly to what may be termed the time factor.

Whatever views are held as to the cause of intergranular corrosion — and the writer considers that the chromium-impoverishment theory ably put forward by Dr. Bain and his colleagues in their paper "The Causes and Prevention of Intergranular Corrosion", and summarized in Chapter 14-B of The Book of



Deep Etched, 4-In. Bar of S.A.E. 4615-A Steel With Oxide Inclusions Indicated. A microsection, properly polished, showed oxide inclusions worse than No. 8 (chart on page 167) and this steel was judged unsuitable for ring gears

Stainless Steels, is by far the most satisfying — there is no question that the structural changes which produce it do not occur instantaneously but require a certain period of time which is shorter or longer depending on the composition of the steel and its prior treatment. In general, these changes occur most rapidly between 1100 and 1300° F., and each particular steel may be regarded as having a maximum "safe period" during which it may be heated in this temperature range without developing any noticeable (or even measurable) reduction in corrosion resistance at the grain boundaries. If this "safe period" is considerably longer than the total time the steel will be heated in the sensitizing range during both its fabrication into plant and the subsequent working life of the latter, intergranular corrosion troubles should not be expected to develop.

As an extreme example, an ordinary spot welding operation on reasonably thin sheet causes the steel to be heated locally for a few seconds at the most, and hence does not impair the corrosion resistance of an ordinary 18-8 steel which may have a "safe period" of about one minute. In the case of plant for which special "weld-decay-free" steels are generally regarded as necessary, this total working time in the sensitizing range of temperature may vary from less than five minutes — for welded equipment, made from sheet or thin plate, which is subsequently used at temperatures not exceeding 600° F. or so — to months or even years when the steel is fabricated into heat exchangers or other plant operating at a dull red heat. In the first case, it would seem obvious that if a steel shows no signs of intergranular corrosion, after heating for 30 min., for example, at 1200° F., followed by 72 hr. immersion in the standard boiling mixture of copper sulphate and sulphuric acid (a drastic corrosion test, but one very frequently used in England), it would possess an ample margin of safety. On the other hand, such a steel might or might not be satisfactory for a heat exchanger dealing with corrosive gases at 1100° F. or thereabouts; indeed such conditions demand a steel as free from intergranular susceptibility as the wit of man can devise.

The thoughts expressed above came to the writer's mind on reading Russell Franks' paper before the Detroit convention ⊜ on "Effects of Special Alloy Additions to Stainless Steels". Speaking of intergranular corrosion and the means of preventing it, Mr. Franks states: "When titanium is used, it must be present to the extent of at least six times the carbon content and the steel must be given a stabilizing heat treatment within the range 1550 to 1650° F. for a period of from 2 to 4 hr. followed by air cooling." Might one suggest that in a great many cases, this stabilizing heat treatment savours of "painting the lily", and that its inclusion as a heat treatment always essential to avoid intergranular corrosion is due to the "time factor" being ignored?

Let it be said at once that if such a steel is to be used under conditions involving prolonged heating in the sensitizing range, the stabilizing heat treatment will probably be necessary to obtain the best results, but if the fabrication of a welded vessel which will never be heated subsequently above 400 or 600° F. is in question, a perfectly satisfactory result should be obtained from this steel without the necessity of subjecting it to the special stabilizing treatment. In the writer's experience, steels of the composition stated, softened in the normal manner at about 2000° F. and then held for 30 or 60 min. at 1200° F., have been free from any signs of intergranular corrosion when tested in the copper sulphate reagent and, therefore, would possess an ample margin of safety for welded plant of the type mentioned above. One agrees that the additional stabilizing treatment would very probably increase the steel's "safe period" and hence the ample margin of safety it already possesses, but to what end? After all, welded plant of this type absorbs a very considerable portion of the total tonnage of "weld-decay-free" steels. Why add unnecessarily to its cost of production?

J. H. G. Monypenny

Nature of Bond
in powder metal compacts

New York, N. Y.

To the Editor of Metal Progress:

Quite early during the study of powder metallurgy the question arose, "What holds particles together after compression?"

In the early days, particularly in the production of tungsten, binders such as molasses or glucose were used to hold the metal particles together until such time as sintering would create a compact mass. The binder evaporates during the sintering.

However, the use of binders had its disadvantages. Porosity was created. Compressed

parts which had little cohesion had to be handled very carefully. Later other metals besides tungsten, molybdenum and tantalum offered commercial possibilities for the application of powder metallurgy. Most of the powders then made were reduced by gas from the metal oxides, and the particles had more or less globular shapes. Powders were used on a large scale in the manufacture of "porous" bearings, and again binders in the form of stearates, oleates, and oxides were used. The fact that porosity was desired permitted the use of globular or rounded particles.

When it was realized that powder metallurgy also offered a field for the production of *solids*, an entirely new problem had to be faced. The need for compressed products of high physical characteristics, in some cases high conductivity, created a demand for non-porous material. Production of powders of different grain structures then became essential and they were made by electrolysis. Powders so produced gave irregular or angular structure. Under pressure these particles interlocked, and this, with close control of particle size, resulted after heat treatment in an almost solid mass. The percentage of porosity was very small and disappeared during later working.

The question "What holds metal powder compacts together without sintering?" occupied the writer's mind continuously. Was it the interlocking of angular pieces, or the deformation of rounded pieces which under pressure filled the interstices?

We must be face to face with phenomena not fully understood. Metal powders, due to their method of preparation and subsequent annealing before use, have or should have very clean surfaces. The friction, during the act of compression, between the clean surface of one particle and the clean surface of another probably develops sufficient heat to weld together the two particles. It is true such welding may be confined to the very surface.

When, however, the friction is between particles of different metals, as for instance copper and tin, the friction causes sufficient heat actually to form an alloy. Migration of atoms into the adjacent fields of metal particles appears to take place. The welded or alloyed bond shows such strength that a slug formed by sufficient pressure could, even before sintering, be thrown with considerable force without breaking apart.

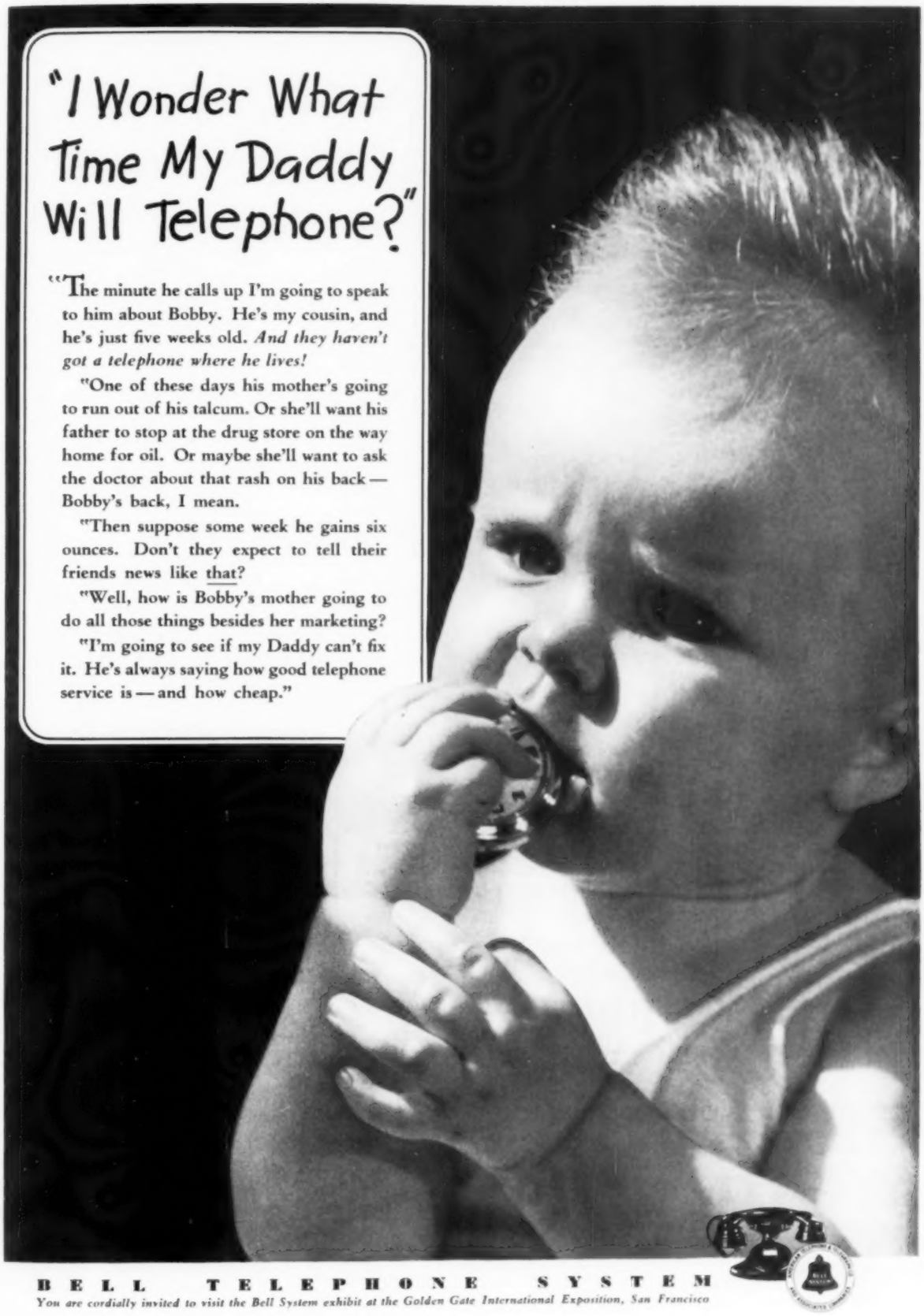
The theory of "atomic welding" or alloying of metal powders was advanced by the writer about three years ago during a talk on Powder Metallurgy before certain chapters of the [illegible]. Since then, however, the writer has found confirmation of his theory not only through observation but also in the work of F. P. Bowden (Metallurgy and The Aero-Engine, Autumn Lecture, 1937, British Institute of Metals) who showed that when two metals were rubbed together even quite lightly, temperatures could be recorded electrically at the surface of contact. When sufficient pressures were applied the temperatures rose quickly to the melting points of the metals and by no increase of load or rubbing speed could the temperatures be made to rise higher.

This initial bonding, welding, alloying or migration of atoms at the very beginning of the operation — namely, the compression — facilitates full diffusion during the subsequent heat treatment.

Powder metallurgy is such a new art that metallurgists engaged in it have to deal quite often with theories whose correctness can only be proven by extensive work, much of which lies in the future. CHARLES HARDY

Ghosts

A Point of Nomenclature: Is it Sorbite, Fine Pearlite, or a Scotty Guarding a Penny? Photo at 1000 dia. of S.A.E. 1025 by Milton H. Grams


"I Wonder What Time My Daddy Will Telephone?"
"The minute he calls up I'm going to speak to him about Bobby. He's my cousin, and he's just five weeks old. *And they haven't got a telephone where he lives!*
"One of these days his mother's going to run out of his talcum. Or she'll want his father to stop at the drug store on the way home for oil. Or maybe she'll want to ask the doctor about that rash on his back — Bobby's back, I mean.
"Then suppose some week he gains six ounces. Don't they expect to tell their friends news like that?
"Well, how is Bobby's mother going to do all those things besides her marketing?
"I'm going to see if my Daddy can't fix it. He's always saying how good telephone service is — and how cheap."
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PERSONALS

Elected vice-presidents of Electro Metallurgical Co.: **James H. Critchett**, who has been in charge of research work, and **Francis B. Morgan**, who has been works manager.

Harold A. Brown is now research assistant, American Steel & Wire, Worcester, Mass.

Lorin L. Ferrall has resigned as metallurgist for Timken Roller Bearing Co. to go with the Rotary Electric Steel Co., Detroit.

George W. Colton has resigned from Yale University to become assistant chief engineer, Crawford Oven Division of American Machine and Foundry Co. in New Haven.

Elected vice-president of Haynes Stellite Co.: **E. E. LeVan**, formerly general sales manager.

Leland L. Pelligren is now employed in the research laboratory of Chicago Steel & Wire Co., assistant to **Oscar E. Swenson**, research metallurgist.

Transferred: **W. N. Thornton**, Lieut. Comdr. U.S.N., from command of U.S.S. Simpson to Norfolk Navy Yard as engineering planning officer.

R. M. Clevenger, laboratory foreman at Farrell Works of Carnegie-Illinois Steel Corp., has been transferred to the Ohio Works as a metallurgist.

Thomas W. Frank, Cornell '38, is now employed in the metallurgical laboratory, Timken Roller Bearing Co.

Robert B. Freeman has been transferred from assistant plant metallurgist at Torrance Works of Columbia Steel Co. to the San Francisco offices as assistant to **G. L. von Planck**, chief metallurgist.

Albert J. Fischer is now with American Cutting Alloys, Lewiston, Me., engaged in chemical analysis and development of powdered metal.

F. K. Ziegler, formerly Chicago district representative of the Electro Alloys Co., is now serving in the same capacity for the Cooper Alloy Foundry Co. of Elizabeth, N. J.

Arthur J. Williamson, formerly metallurgical assistant, John A. Roebling's Sons Co., Trenton, N. J., has been added to the technical staff of Summerill Tubing Co., Bridgeport, Pa., as metallurgical engineer in charge of research and development.

Richard Hammerstein is now with the metallurgical department of the Gary sheet mills of Carnegie-Illinois Steel Corp.

Walter A. Janssen has been appointed chief, Metals and Minerals Division, Bureau of Foreign and Domestic Commerce, Department of Commerce, Washington, D. C.

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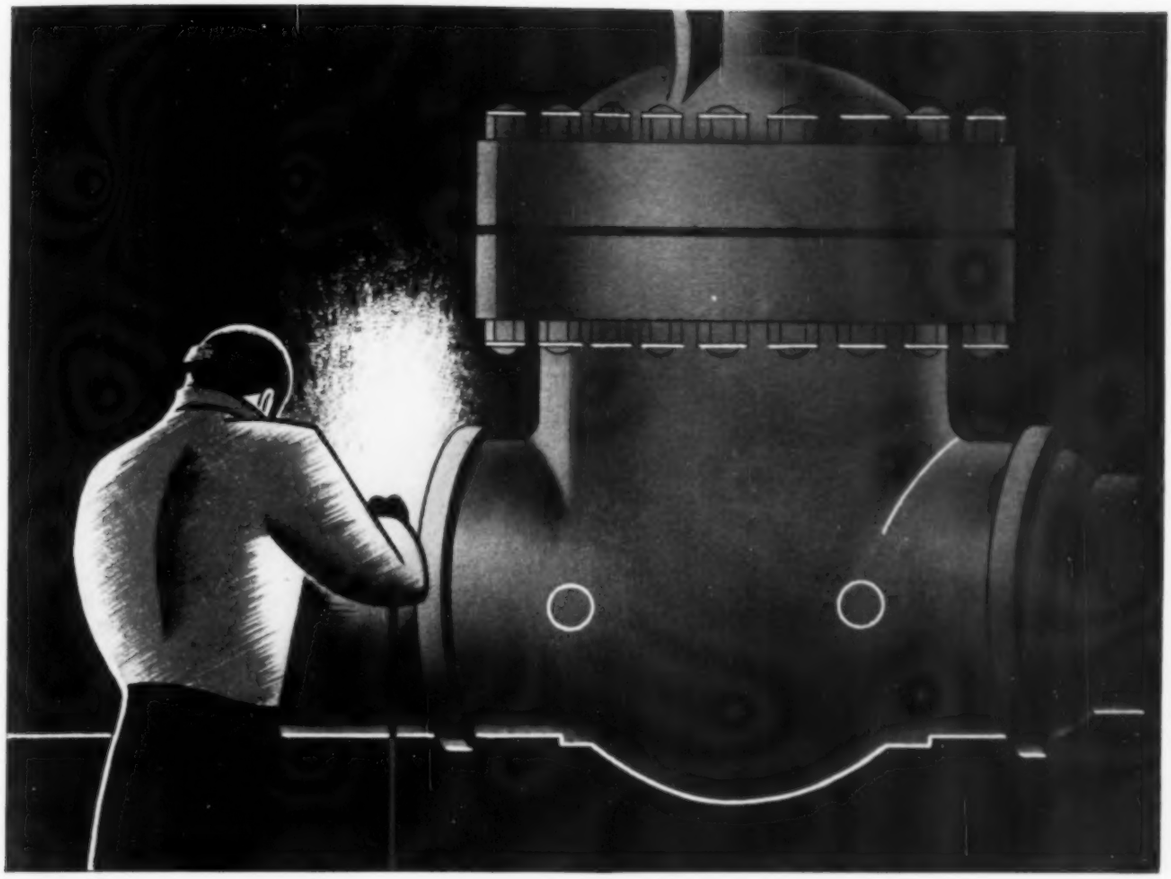

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MOLY

PERSONALS

L. B. Ely is now manager, process service department, Southern Division, The Linde Air Products Co., in Birmingham.

Howard O. Nordquist is now an open-hearth metallurgist at Inland Steel Co., Indiana Harbor plant.

Transferred: **Felix F. Aloi**, from strip mill metallurgist, Lackawanna plant of Bethlehem Steel Co., to central metallurgical division at Bethlehem as assistant metallurgical engineer, covering sheet and tinplate products for all plants of Bethlehem Steel Co.

Promoted: **William P. Knecht** to European manager for the Crucible Steel Co. of America with headquarters in London.

C. O. Fairchild, Director of Research for C. J. Tagliabue Mfg. Co., Brooklyn, has been appointed chairman of a committee to organize an extended symposium on temperature measurement by the American Institute of Physics.

Lt. Charles B. Martell, U.S.N., is concluding the third year of Naval postgraduate work in ordnance metallurgy, including tour of various plants engaged in Navy work.

Kenneth Lewis is graduated from Michigan College of Mining and Technology and is now working at the Rotary Electric Steel Co., Detroit.

Promoted: **D. J. Richards**, past chairman, Pittsburgh Chapter, from divisional sales manager to manager of steel mill sales for E. F. Houghton, Philadelphia.

A. B. Lindsay, for the past 20 years with Strong, Carlisle & Hammond Co., announces the formation of Lindsay & Co., for engineering and building industrial furnaces and equipment.

J. J. Beinlich has been made metallurgical observer in the Clairton Works, Carnegie-Illinois Steel Corp.

Robert M. Irving, formerly with Hammond & Irving, Inc., Auburn, N. Y., has opened his own forging plant in Syracuse, the Irving Forgings Co.

Walter M. Albrecht, formerly assistant metallurgist at the American Hoist and Derrick Co., St. Paul, is now connected with Chain Belt Co., Milwaukee.

Harold McCrensky, M.I.T. '38, is now employed by the Peninsular Grinding Wheel Co., Detroit.

John L. Burns is now assistant superintendent of the Wire Division of Republic Steel Corp., at the Grand Crossing plant in Chicago.

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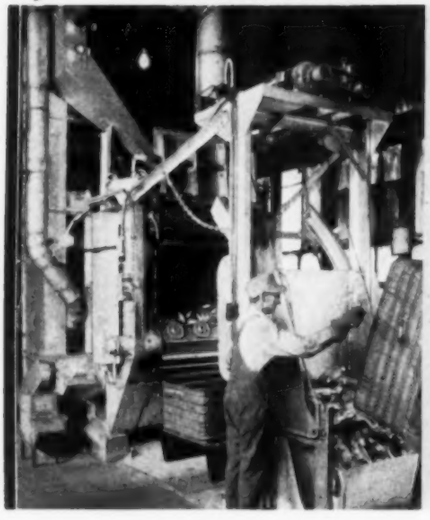

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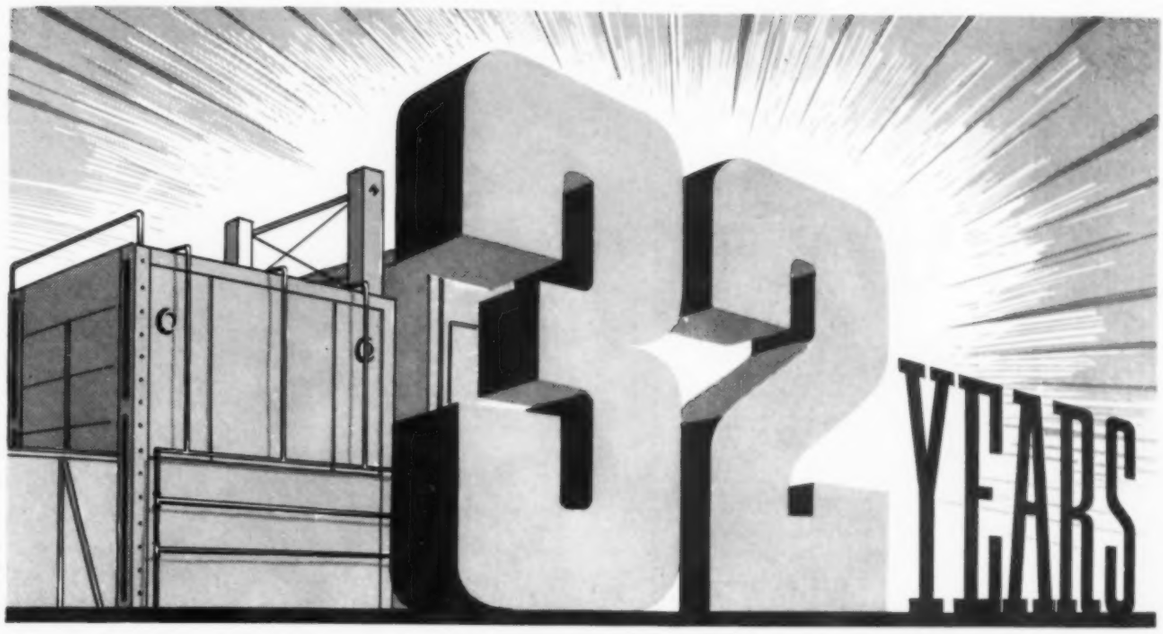

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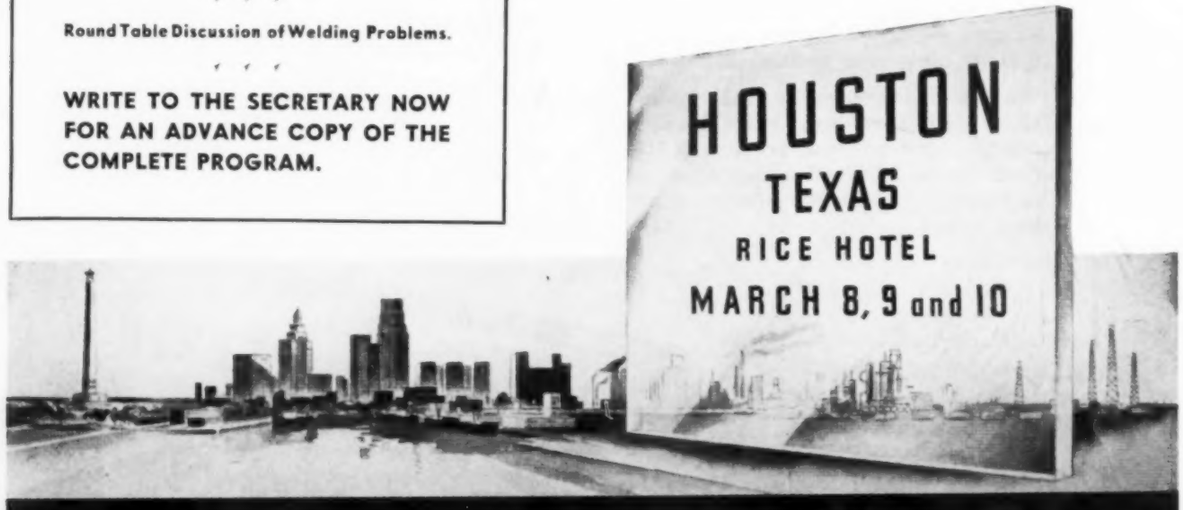
EVERYONE interested in the application or operation of the oxy-acetylene process may attend and profit from the 39th Convention of the International Acetylene Association, which meets this year at Houston, Texas. Meeting on March 8, 9 and 10, the convention presents an opportunity for you to prepare money-making and money-saving ideas in the early part of what promises to be a year of increased business activity.

Recent developments and trends in the uses of the oxy-acetylene process will be reviewed, co-ordinated, and discussed by foremost engineers and practical operators. A glance at the High Lights on the left will indicate how timely and important are the subjects to be presented.

If you have attended the conventions during recent years, you will want to come again. If you have never attended the conventions, you owe it to yourself and your business to find out how valuable they are to users of the oxy-acetylene process. All sessions are open to everyone interested. There is no registration fee.



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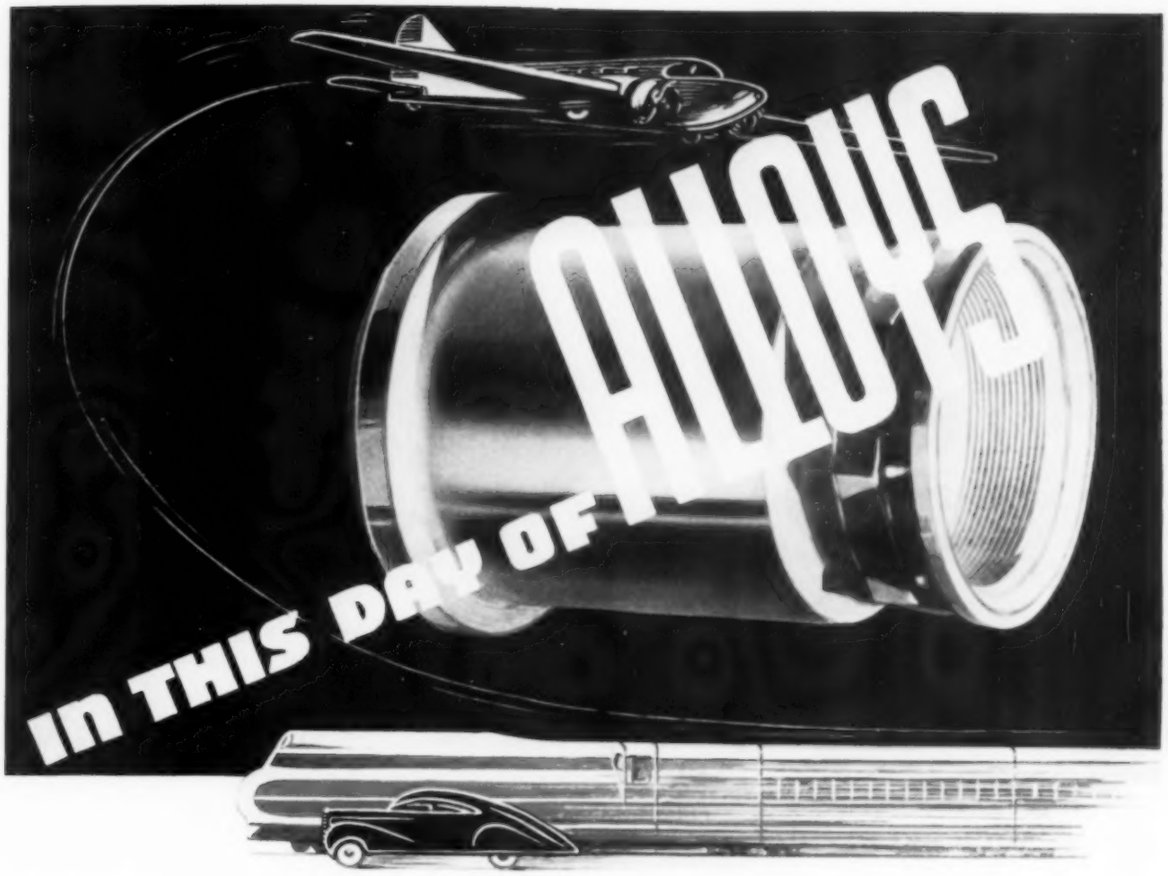

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S FROM PIG

(Continued from page 146)

hot ladle where, due to its high melting point, it would be released slowly upon the addition of hot metal.

Results of tests in graphite or fireclay crucibles show that more than 80% of the sulphur in molten pig iron at 2550° F. (1400° C.) is removed in 3 min. by equal parts of calcium carbide and common salt. For this reaction 20 lb. of the mixture per ton of iron was necessary. Originally the various lots of iron contained 0.06 to 0.16% of sulphur; in all experiments the resulting iron contained 0.015% sulphur or less. These results may be considered the goal to be reached by the proper manipulation of CaC_2 in the desulphurization of larger amounts of metal.

As a check on the crucible treatment and to obtain data on the desulphurization of larger amounts of metal, 150-lb. charges of metal were melted in an electric arc furnace and desulphurized in the same manner as the crucible tests. Initial sulphur in these original irons was fairly low, but even so more than half of it was removed in 8 min. by an equal mixture of carbide and salt in the proportion of 20 lb. per ton of iron. Representative tests are, 0.056 sulphur to 0.022; 0.063 down to 0.025; 0.049 down to 0.021; 0.039 to 0.015; 0.026% S in original iron to 0.012% after treatment.

Average temperature of the iron during the test was within the range 2450° F. and 2550° F. (1337° C. and 1400° C.). The value of these temperature measurements is to show that desulphurization can be accomplished at temperatures in the blast furnace ladle or in the mixer.

Minor changes in metal composition during desulphurization with carbide are noted. Manganese and silicon are affected much less by this treatment than by alkali desulphurization, although both elements show a small decrease. The carbon content shows a small increase in most cases, which is accounted for by the carbon pick-up from calcium carbide. The phosphorus was virtually unchanged.

Desulphurization by other carbides has been considered, but calcium carbide appears to be the most suitable for the treatment of pig iron. Preliminary experiments show that low carbon steel may also be so desulphurized.

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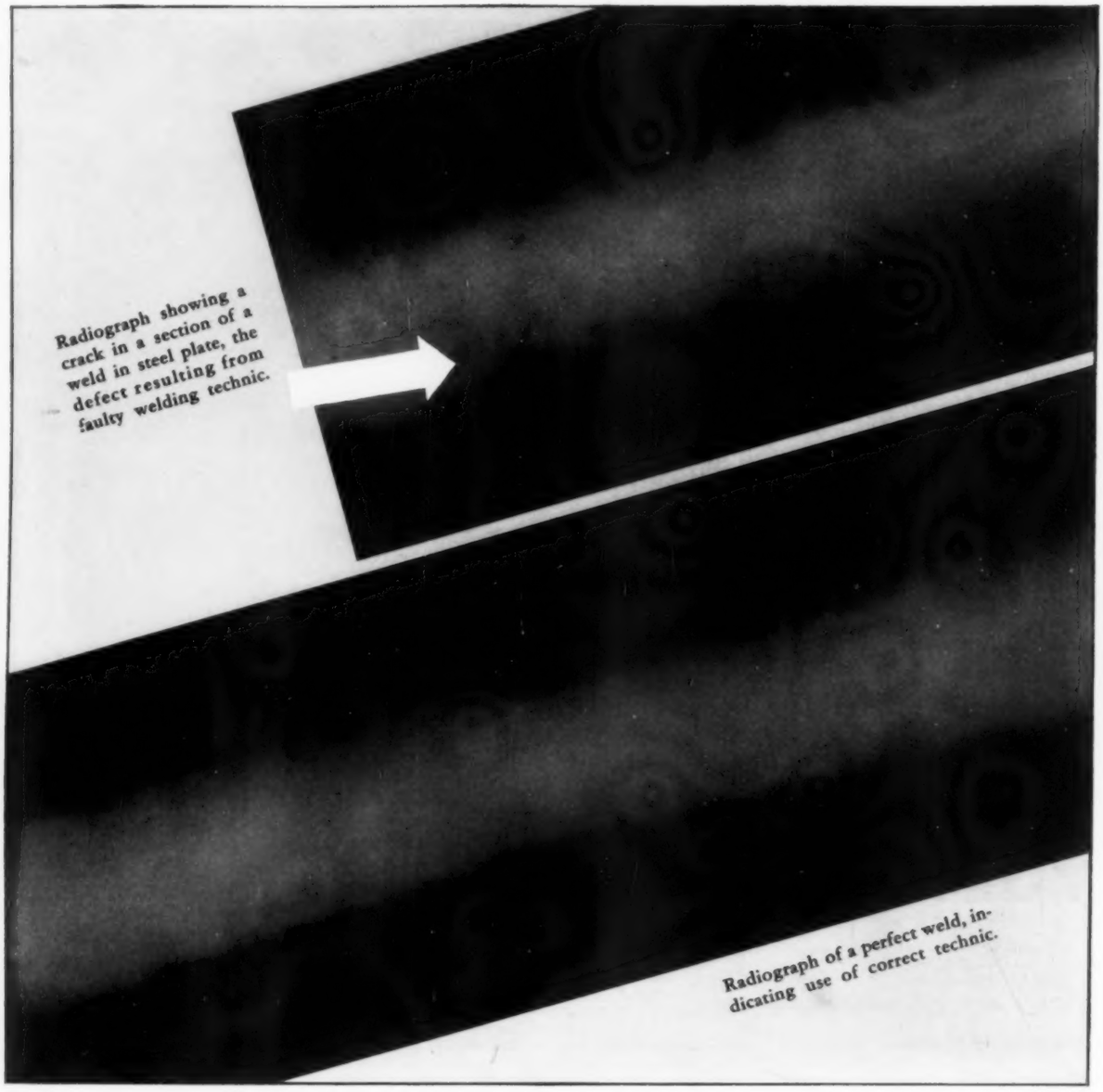
Radiograph showing a crack in a section of a weld in steel plate, the defect resulting from faulty welding technic.
Radiograph of a perfect weld, indicating use of correct technic.

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BY

Waldemar Naujoks, B. S., M. E.
Chief Engineer, The Steel Improvement & Forge Co.
Cleveland, Ohio

Donald C. Fabel, B. S., M. S.
Head of Mechanical Engineering Department, Penn College
Cleveland, Ohio

SECTION HEADINGS

The Forging Industry
Forge Plant Equipment
Die Block and Process Operations
Forge Dies and Tools
Forging Practice
Finishing Operations
Heat Treatment of Forgings
Cleaning of Forgings
The Testing and Inspection of Forgings
Materials Handling
Forge Plant Design
Forge Plant Maintenance
Furnaces and Furnace Design
Designing the Forged Part
Forging Materials
Job Estimating
Costs and Cost Engineering
Forge Shop Safety
Forging Definitions
Mathematical Tables and Data

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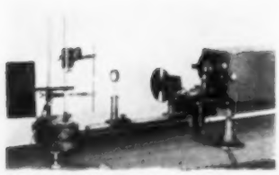

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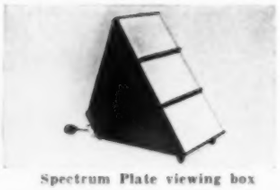

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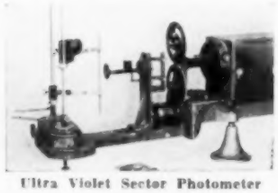

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TIN COATINGS

from vapor

(Continued from page 155)

the amount of coating per unit time increases slowly up to about 1025° F., above which the action increases quite rapidly. The speed of deposition probably represents the diffusion rate or the ability of the copper to saturate itself with tin under any given temperature condition. As the sample is heated to higher temperatures, diffusion becomes increasingly rapid and a deeper layer of tin-copper alloys is formed.

A little moisture in the atmosphere is harmless. Natural gas, CO, nitrogen and steam are unsatisfactory atmospheres. In a large-scale operation an atmosphere of hydrogen and tin chloride would be circulated over the work and then back to a body of metallic tin; in such a regenerative cycle the gas can be conserved and its cost minimized.

Tin is undoubtedly deposited as pure tin on the surface of the material being coated. Since it is molten and at a temperature sufficiently high for an alloying action to take place with most metals, the tin does not long remain pure unless the rate of deposition is much greater than the rate of diffusion. One would consequently expect the coating to consist largely of a tin alloy of composition dependent on the factors governing diffusion, that is, temperature, time, and character of the basis metal.

With copper as the basis metal, the coating may have a complicated structure or consist of a series of bands due to the many tin-copper intermetallic compounds, to phases that undergo decomposition on cooling, and to the tendency for alpha bronze to form next to the copper. The actual reaction at the surface is very simple: $SnCl_2 + H_2 \rightleftharpoons Sn + 2HCl$, a reaction which is "catalyzed" to proceed from left to right by contact with a second metal, and which is reversed (regenerated) by contact with pure tin.

Other metals and alloys were effectively stannized, such as bronzes and brasses. Steel acquired a thin but fairly continuous coat in 30 min. at temperatures between 950 and 1025° F.; at 1110° F. a heavier, more granular deposit was obtained. Zinc and its common alloys were also stannized.

Tin is not deposited by the stannizing method on glass or refractory material. Occasionally, however, droplets of tin are noted on ceramic material at a few points where it is suspected that local impurities are reduced to metal by the hydrogen atmosphere. Apparently a metal surface is needed to activate the decomposition of the volatilized tin compound.

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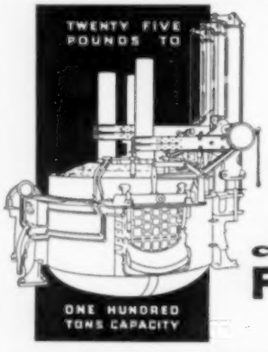

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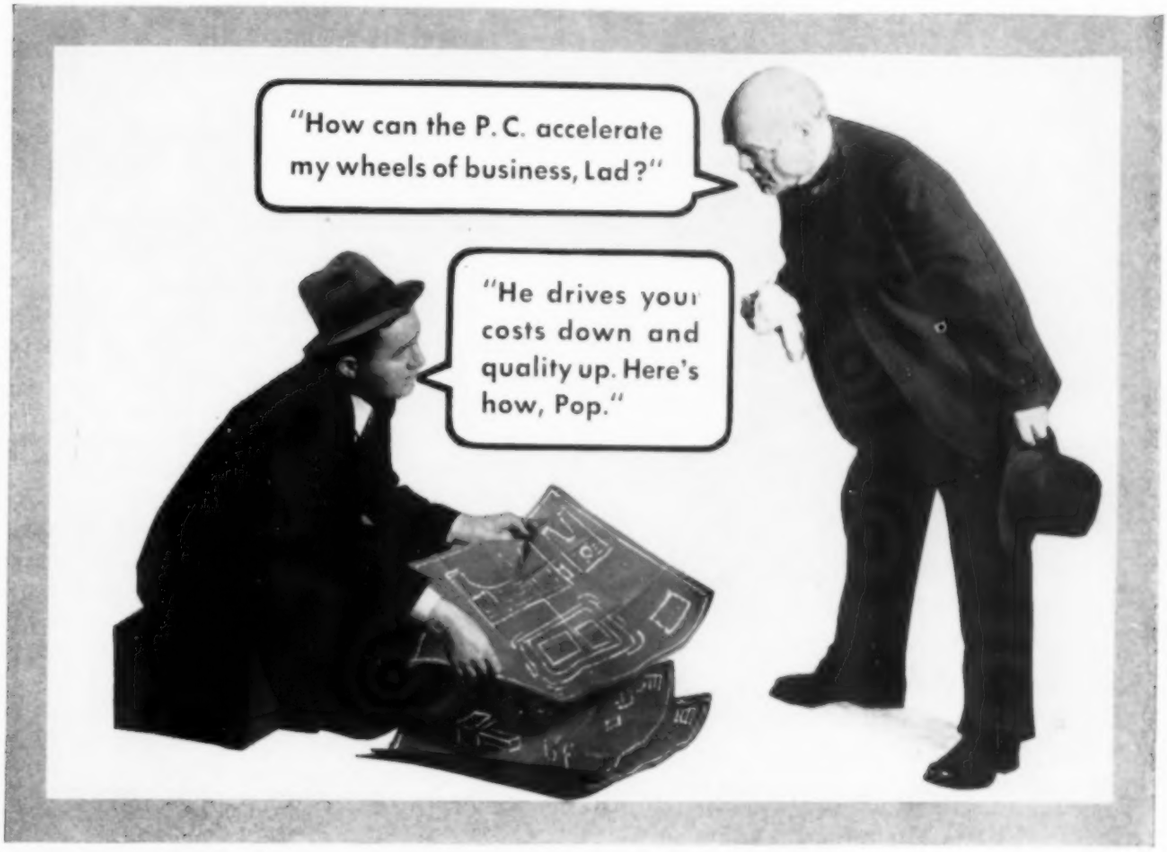

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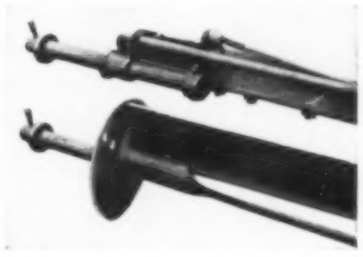
"Here is an example of the work of the Profit Crusader in one plant. The part is an axle of a hay rake, formerly consisting of an assembly of castings and truss rod which frequently became loose in service, requiring repair. The Profit Crusader took an angle iron, flat bar and plate and welded them into a permanently rigid unit. The farmer got a shimmy-proof hay rake and the manufacturer saved 30% on the part.

"There's an attractive booklet



available for the asking which gives some valuable suggestions for the Profit Crusader. Write for a free copy. And by all means, get in touch with the nearest Lincoln office. These people will do you and your wheels of business many a good turn."

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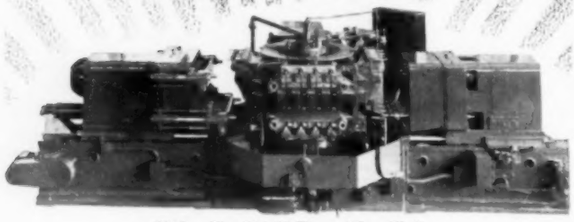

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This remarkable Baker machine takes care of four operations, accurately and at high speed—drilling, reaming, chamfering, and tapping—on steering handle support arms. Gear trains must be built to "take it" and that's why Baker chose Ampco Metal for vital gears.

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RIMMING STEEL

(Continued from page 147) and the whole structure indicates a gradually increasing pressure during solidification.

The effects of pressure are evident in the region of the intermediate holes which form just after the top surface of the ingot has completely frozen over. These holes are usually accompanied by irregular segregates of impure metal which has been squeezed out from the semi-solid mass of steel to fill or partly fill them. A fairly definite "upset" structure can be seen in this region, resulting from deformation by the great pressures developed within.

A number of special conditions of freezing were investigated. Early capping of the ingot shifted the line of intermediate holes nearer to the surface so that they coincided with the inner end of the rim holes. The central region of this capped ingot was phenomenally sound. The reverse procedure, keeping the ingot open by insulating the top, produced a spongy top and large core holes. Oscillation of the mold around its axis during rimming produced an ingot with two distinct sets of intermediate holes.

In addition to the very detailed study of the structure of the ingot, the report contains data on rate of freezing, gas evolution, segregation and non-metallic inclusions which, in general, are in agreement with results reported by investigators in England and America. These observations form the basis for a detailed discussion of the mechanism of solidification and blowhole formation which clarifies many formerly obscure features of ingot structure.

The final section of the report contains a discussion of various factors influencing the rimming process. The authors' conclusions in this regard are in agreement with experience in this country. Briefly they state that:

Sufficient over-oxidation to produce copious gas evolution will tend to produce ingots with a sound rim zone.

In rising steel, which is under-oxidized, the rim holes may extend to the top of the ingot.

A high casting temperature leads to retention of gas and thinner skin.

A low casting temperature favors rapid gas evolution and thicker skin.

A slow casting rate, especially very slow filling of the mold as when bottom pouring a group of ingots, permits more gas evolution and is conducive to thicker skin.

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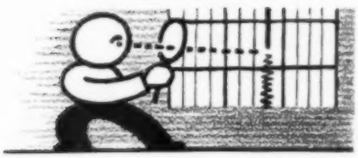
The Wheelco Radio Principle Proportioning Controller

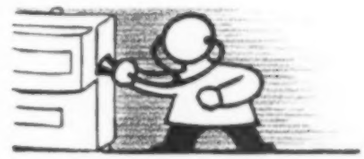


*Completely eliminates time lag between temperature deviation and control action, affording highest efficiency from your furnace investment.

*There are no moving parts to wear out or interfere with control efficiency.

*Effects 80% closer control than the highest priced mechanical controller on the market.

*Sells in the lower price ranges, due to its simplicity of construction.



Time lag between temperature deviation and control action, together with lost motion caused by wearing parts in your controller, will materially affect the output of your furnace and establish needless wear and tear, which in the final analysis can only appear on your books as loss.

Stop this loss with the CAPACITROL. The initial cost is low. Its simple construction, free of moving parts, assures long dependable service and efficiency far surpassing that of all other known instruments and your furnace investment produces materially increased returns in less working hours.

The CAPACITROL is producing astonishing results in every department of temperature control. It is the only controller that assures successful operation under all service conditions, due to its simple wiring circuit and one tube design.

Complete data, description and illustrations forwarded promptly on request.

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NOTES ABOUT CONTRIBUTORS

Born in Ann Arbor in 1902, **Hudson T. Morton** naturally attended University of Michigan, graduating in 1924 with a B.S. in Chemical Engineering. He became affiliated with the Hoover Steel Ball Co. as chemist and in 1927 was promoted to metallurgist. In 1936 he became chief metallurgist of the renamed Hoover Ball and Bearing Co., handling the usual duties pertaining to inspection and testing of raw materials, heat treating procedure, and research. He has written articles on strip steel, stainless steel, and similar subjects which have appeared in **Metal Progress**, **Transactions**, and trade and technical magazines.

The new application of arc welding described by **Robert E. Kinkead** in the leading article in this issue is a result of his work as consulting engineer in welding for Carnegie-Illinois Steel Corp. over a period of about two years. For this paper he received the third grand award of nearly $9000 in the Lincoln Arc Welding Competition, and thus became the envy (if not the inspiration) of consultants everywhere. Mr. Kinkead, a graduate of Ohio State University, has been a Cleveland consulting engineer in welding for many years. Some years ago he prepared an engineering appraisal of the welding processes which appeared in **Metal Progress** in four installments.

Now technical consultant to the sales department for A. O. Smith Corp., **T. McLean Jasper** has been well grounded in the mechanics of materials. A graduate of University of Illinois, he had a few years' technical experience before joining the Royal Field Artillery during the World War. After the Armistice a year was spent as assistant professor of mechanics at University of Wisconsin and five years as research associate professor of engineering materials at University of Illinois. In 1926 he joined A. O. Smith Corp. While at Illinois, he also acted as engineer of tests for the National Research Council on its Fatigue of Metals Investigation, and is the author of several bulletins on this subject as well as many other papers on high temperature strength of steel, welded pressure vessels, elastic problems and associated engineering mechanics.

"By his many successful investigations into the physical and chemical properties and behavior of metals and alloys, and especially by his invention and development of gamma-ray radiography, he has rendered extraordinary service to American industrial enterprise," said in part the citation accompanying award of the honorary degree of D. Sc. to **Robert F. Mehl** by Franklin and Marshall College last spring. Mehl received his B.S. from that institution in 1919 and his Ph.D. from Princeton in 1924. From 1923 to 1925 he acted as head of the department of chemistry of Juniata College, and was a National Research Fellow at Harvard University from 1925 to 1927. After short periods as superintendent of the division of physical metallurgy, Naval Research Laboratory, and as assistant director of the research laboratories, American Rolling Mill Co., he joined Carnegie Tech in 1932 to direct the Metals Research Laboratory. Since 1935 he has headed the Department of Metallurgy.

George Warren Walker retired about a year ago from active work, and "is enjoying a library of some 800 volumes accumulated in the course of about 50 years"—as he says and as he might have added: "This were paradise enow!" He worked out the method for rating steel by non-metallic inclusions shown on the data sheet, page 167 and described in his letter on page 169 during the 12 years he was in charge of the metallurgical laboratory of Chevrolet Motor Car Corp.

Hudson T. Morton

Robert E. Kinkead

T. McLean Jasper

Robert F. Mehl

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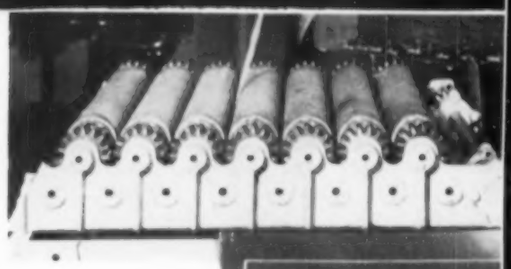

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Removable Like a Drawer
Reduces Roll Span
Eliminates Holes in Furnace Wall

A Real Advance
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PAT. PENDING

NEW YEAR'S morn found me packed among the celebrants on the Chicago-New York air sleeper. Mrs. H. flew my ship from Boston, met me at Newark, and in ten hours and five minutes flying time—presto—Orlando, Fla., for the sixth annual "Flying Alligators" air party, where over 500 private flyers congregated from points including Canada and South America. Imagine 500 planes, flown by private owners, many only student pilots, on one airport! 30 or 40 ran out of gas, made forced landings. One girl landed in a field, "bummed" a gallon of gas from a farmer's tractor to fly her Cub 20 miles into Jacksonville. 30 planes, half without lights, landed at night. At 9:15 P. M. a 63 year old grandmother, flying her own Aeronca, accompanied by a bull pup and flying by road map, arrived safely. The Department of Commerce ran out of maps and many of the flyers came in without maps of any kind, a dozen or more without compasses. Not an accident! 200 new initiates to the Flying Alligators Club walked barefoot among real alligators, and a goose or two. Then to Miami for the air races.

LADY pilots found Florida resorts inadequately maled.

WIDE WORLD photos released my aerial photos to 200 papers, including *Time*. Bernarr MacFadden staged a huge "hawg rassle", called a "Pilots' Ball" at his MacFadden-Deauville, ex-gambling joint, on Miami Beach, Florida's cross twixt Coney Island, Hollywood, and the Bronx. Pilots mistook salons for saloons and vice versa. Flying over the Everglades is good for the soul, gives you faith in the Motor. 40 planes participated in the hop to Havana.

CUBA'S President staged a party for American pilots that made the "risk" inconsequential. Have been traveling with Oscar and Emeline, baby alligators. Bathing four times a day they bark like Chihuahuas, sleep for an hour if you rub their tummies. In 20 years they'll make Gladstones. We can't tell the poppagators from the propagators.

AT Jacksonville airport a hungry hound made plaintive plea for food. Embarrassed by my lack of bones, remarking, "I wish I could give that mutt a nickel to buy a hamburger." A small cullud boy spoke up, "Dat's O. K., mister, but wrap it in paper so's old Soc cahn't swallow it." I wrapped a nickel in a film tab and gave it to "Socrates"—a wise hound—who gallumped to the "dog" stand, surrendered the nickel, received his hamburger.

PHOTOED below shot of Beechcraft turning pylon at 210 M.P.H., standing on pylon the "wash" took the lining out of my tie. With me loafing, G. A. should make money in January and February. —H. H. H.

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Runs on top of a rail—returns in the same rail. The simplest and best light load conveyor.

INNER-SEAL POT
at last a tight flange seal!
a Knife edge Valve Seat
TOP INSULATION
(H.H.H. Patents Pending)
This double section of the air-line greatly increases pot life where 90% of all failures occur.
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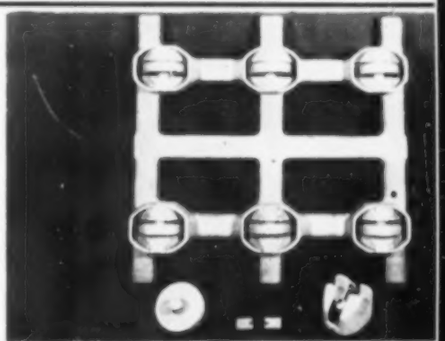

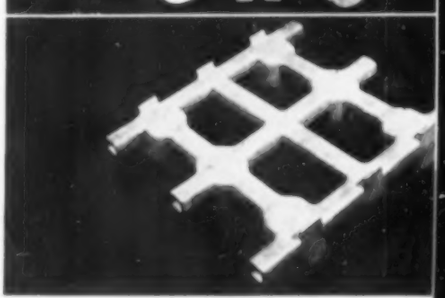

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RECRYSTALLIZATION

(Continued from page 159)

ature for cold-worked iron. Recrystallization does not occur below 460° C., and the temperature where it begins increases with decreasing deformation until A_3 is encountered. This diagram, obtained for deformation at the temperature of recrystallization, differs from a diagram for deformation at room temperature and recrystallization at the designated temperature only in degree — the general form is the same, as indeed it is for all metals and alloys. Therefore, for degrees of deformation and annealing temperature to the left of and below the curve no recrystallization occurs, no change in the grain structure can be detected; in this range recovery occurs.

The exact position of such a curve will vary with a number of factors including the type of deformation, the original grain size, and purity. Even slight differences in purity exert a wholly disproportionate effect. It is ordinarily difficult to determine the applicability of published data to a given material, for frequently important variable factors have been disregarded.

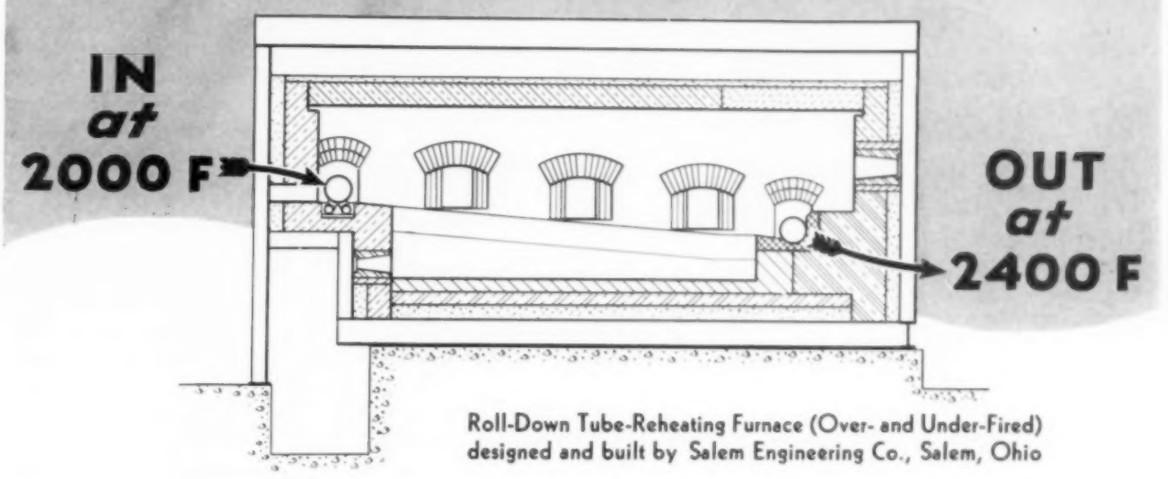
The grain size developed on heating samples which have been deformed to increasing degrees is especially instructive. The middle curve on page 159 shows that a "critical" deformation of about 7% is required before any change in grain size occurs in low carbon steel. This formation of large grains on recrystallization at the minimum deformation is probably caused by the occurrence of a minimum of nuclei; at degrees of deformation below this the number of recrystallization nuclei becomes disappearingly small; with increasing degrees of deformation, an increasing number of points of high stress (high energy) are present, leading to a greater number of nuclei, a greater number of grains, and a smaller grain size.

The last figure shows that for a constant annealing temperature shorter times are required for recrystallization at higher degrees of deformation, and shows also that with increasing temperatures lower degrees of deformation and shorter times are required for recrystallization. Such generalizations are applicable when the type of deformation is simple, as, for example, increasing amounts of compression, but when several types are superimposed, or when reversed deformation occurs, the recrystallization tendency is decreased even though reversed deformation may continue to work harden the metal. The reason for this phenomenon is not clear.

The effect of original grain size on recrystallization can readily be understood. The amount of strain hardening which a given amount of com-

(Continued on page 194)

50 Tons per hour



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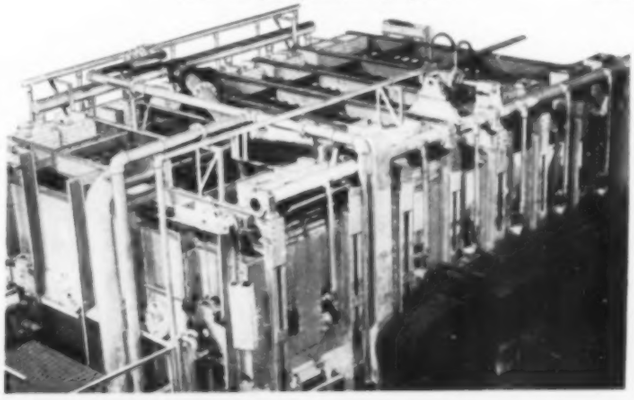

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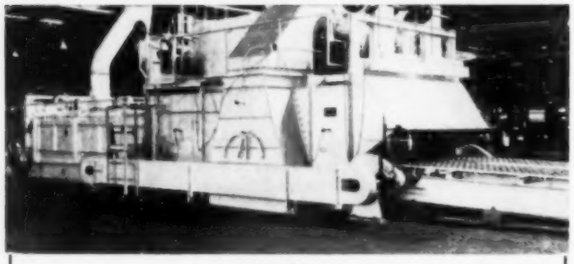

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RECRYSTALLIZATION

(Starts on page 156)

pression, elongation, or torsion introduces into a metal increases as the grain size decreases. When, in a given metal at a single temperature, equivalent amounts of strain hardening are introduced, requiring large amounts of deformation for large grained metals and small amounts of deformation for small grained metals, the recrystallization behaviors are apparently identical.

The relationships between degree of deformation, annealing temperature, and resultant grain size have frequently been assembled into a three dimensional chart. They are commonly derived from data obtained using constant (and short) annealing times; furthermore, the factor of original grain size is not represented. A five dimensional chart would be required to show all of these relationships. This limitation of three dimensional diagrams, the occasionally extreme effects of minor amounts of impurities, and the complications introduced by the complexities of industrial forming processes with resultant complexities in internal stress distribution, render such charts of little direct practical use. They should be used only to indicate the recrystallization behavior of a material in a roughly qualitative way.

Recrystallized cold-worked metals can exhibit preferred orientations and directional properties, though they may not be identical with those which characterized the metal before recrystallization. Relatively little is known concerning the inheritance of preferred orientations during recrystallization and no generalizations can be made.

Impurities in solid solution exert a pronounced effect upon recrystallization temperatures. The relatively minor variations in composition in the several varieties of copper have been noted. Increasing concentrations in solid solution become increasingly less effective until, in a completely isomorphous system, a maximum recrystallization temperature is reached at an intermediate composition, which may be far above those of the component metals. It has frequently been stated that impurities which do not form solid solutions have little effect on softening and recrystallization temperatures; this generalization is somewhat doubtful, for at least in the case of aluminum alloys such impurities are employed to raise the temperatures required for recrystallization, and when present in a sufficiently fine state of subdivision are more powerful in this respect than elements in solid solution.

Grain Growth — The curves for copper on page 157 show softening and recrystallization to have been completed at 400° C., but show also an increasing grain size on heating beyond this temperature.

(Continued on page 196)

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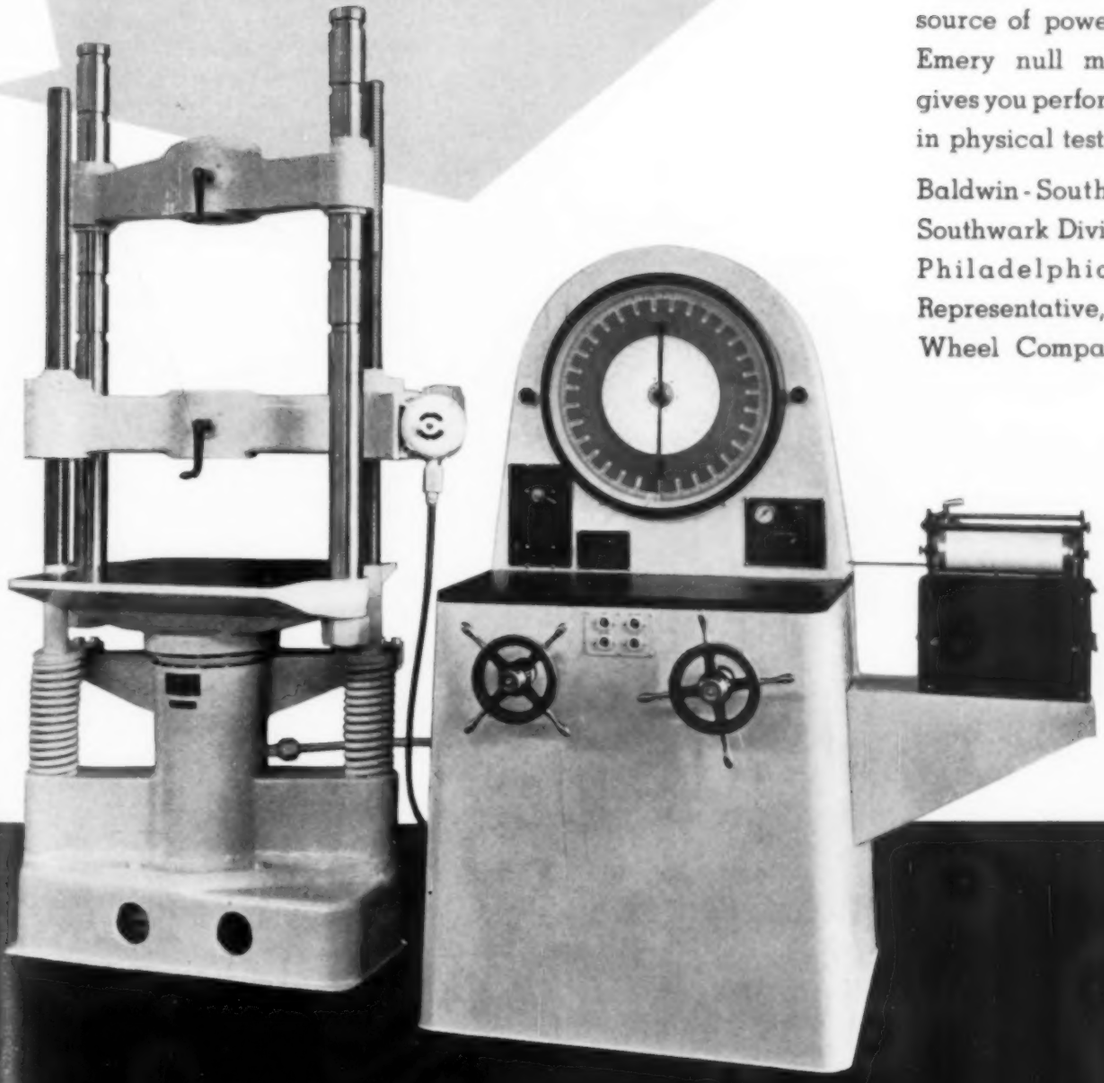

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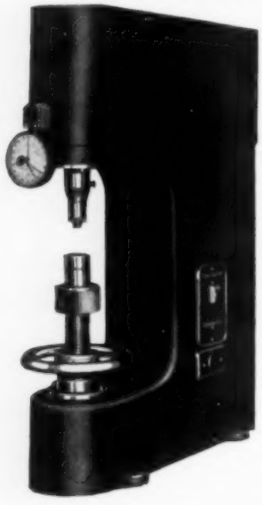

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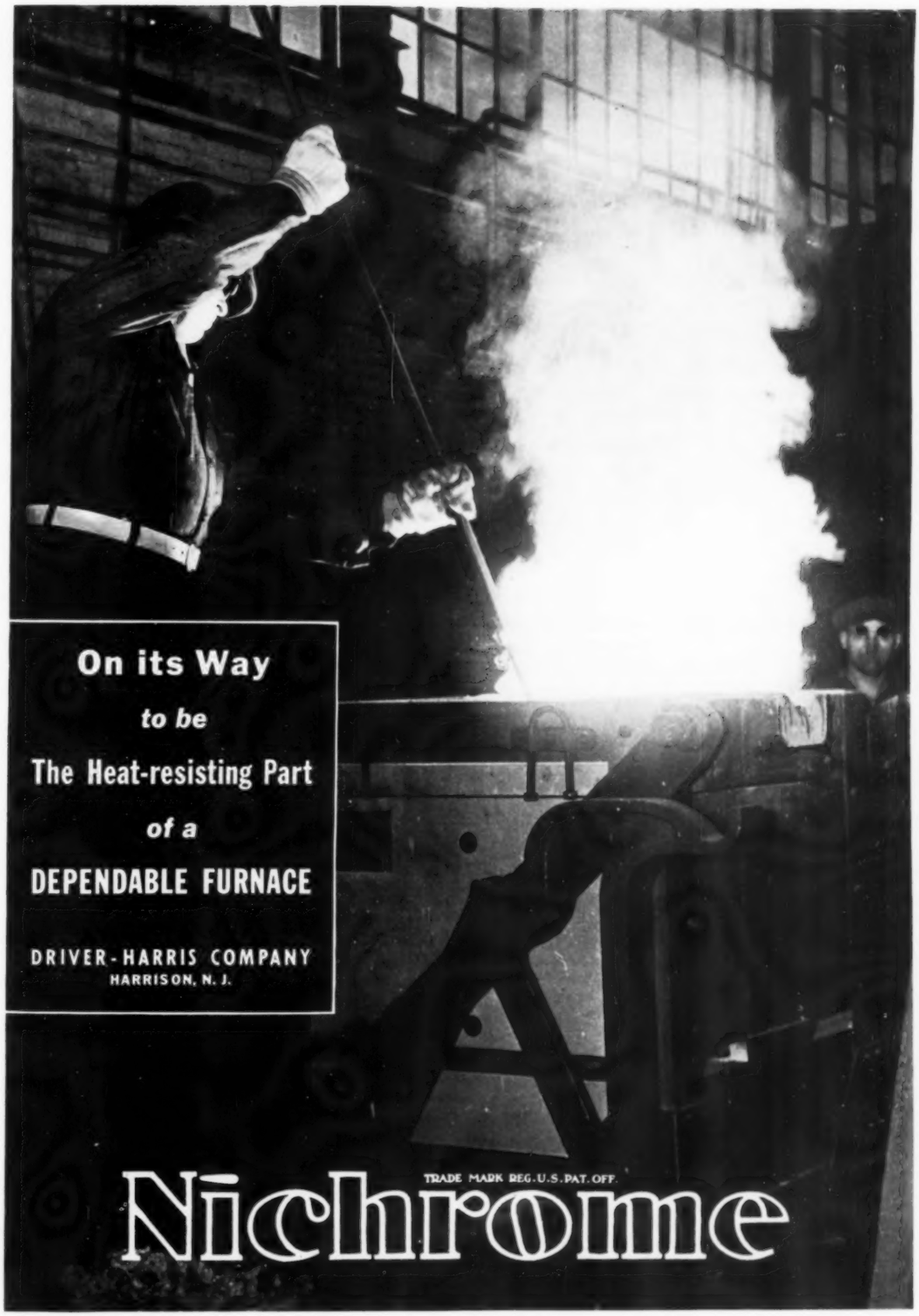
RECRYSTALLIZATION

(Starts on page 156)

This growth of grains in a completely recrystallized and strain-free structure is known as grain growth. It proceeds in an endeavor to decrease the grain boundary area and thus the internal energy. Grain growth proceeds by the absorption of smaller by larger grains, and doubtless accompanies and overlaps recrystallization, as defined above. It is especially noticeable following the recrystallization of severely deformed aggregates, for the grain size after recrystallization in this case is small and grain growth is readily noted, whereas in samples recrystallized after slight deformation the original grain size is large and the subsequent grain growth is minor. Slow heating favors the growth of large grains, which in some cases may become very large.

Impurities in solid solution have a minor effect on grain growth, but undissolved impurities exert a pronounced effect. With very pure substances grain growth proceeds steadily, with the average grain size increasing with increasing annealing temperature. But if undissolved impurities, such as thoria in tungsten, iroa in aluminum, lead in zinc, are present in the proper amount, the grain size is then small at low temperatures and suddenly increases in a narrow temperature range forming unusually large crystals; when the amounts are larger, grain growth may be entirely prevented. Thus immiscible impurities may be used either to suppress grain growth at relatively low temperatures or to create unusually large grains at higher temperatures.

Bibliography — The bibliography on recrystallization is extraordinarily voluminous, and it is unnecessary to reproduce all of it here and useless to reproduce only selected references. The most complete summaries are those given by G. Sachs, "Praktische Metallkunde, v. II, Spanlose Formung", published by Julius Springer, Berlin, 1934; and E. Schmid and W. Boas, "Kristallplastizität", published by Julius Springer, Berlin, 1935. Sachs gives a complete summary except for iron and steel, while Schmid and Boas stress the scientific aspects of the subject. Data on the recrystallization of iron and steel may be found in P. Oberhoffer, W. Eilender and H. Esser's book on "Das Technische Eisen", Julius Springer, Berlin, 1936; and E. Houdremont, "Sonderstahlkunde", Julius Springer, Berlin, 1935. The material in the present paper has been drawn largely from these sources. An extensive bibliography on the recrystallization of iron and steel has been given by H. F. Kaiser and H. F. Taylor: "The Effect of Cold Deformation on the Recrystallization Properties of Armco Iron", American Society for Metals, preprint, 1938 fall meeting.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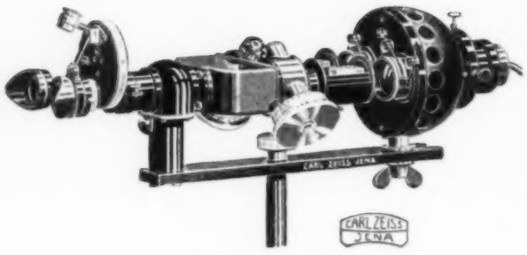

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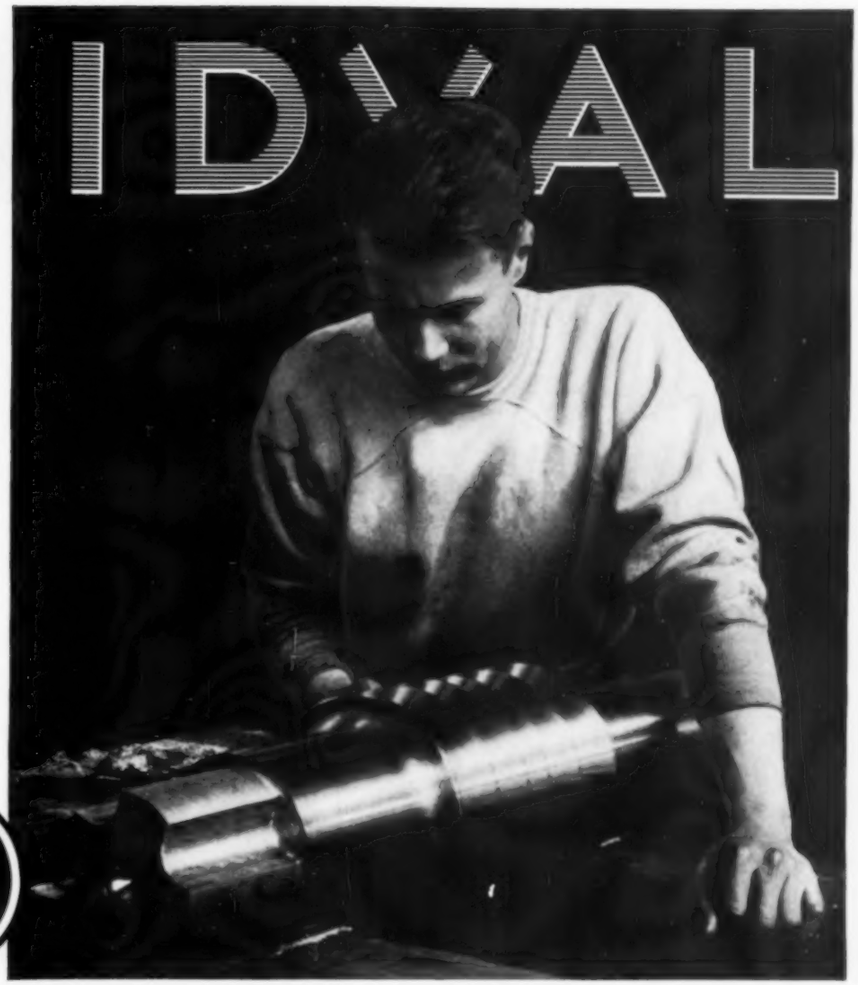

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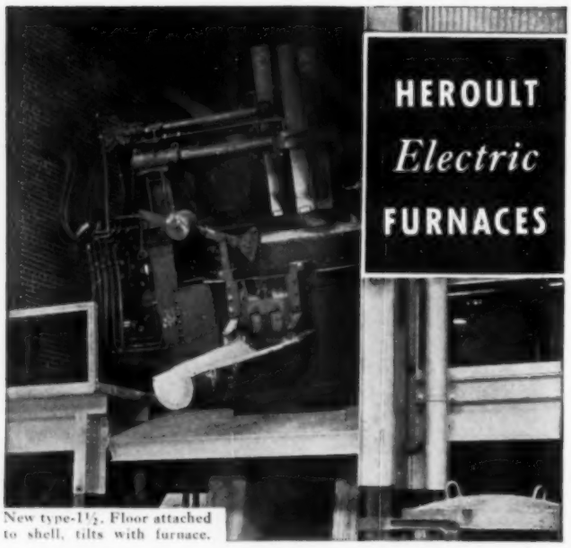

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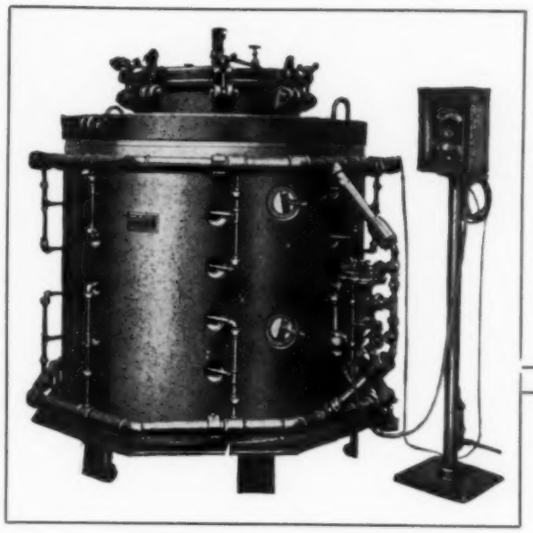

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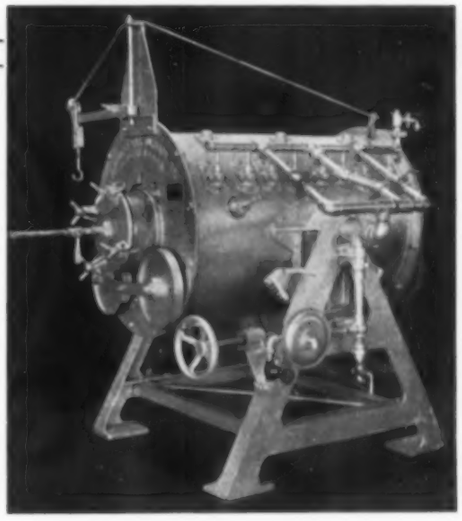

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